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**Small-volume basaltic volcanoes: eruptive products and processes, and post-eruptive geomorphic evolution in Crater Flat (Pleistocene), southern Nevada**

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**Abstract**

Five Pleistocene basaltic volcanoes in Crater Flat (southern Nevada) demonstrate the complexity of eruption processes associated with small-volume basalts and the effects of initial emplacement characteristics on post-eruptive geomorphic evolution of the volcanic surfaces. The volcanoes record eruptive processes in their pyroclastic facies ranging from "classical" Strombolian mechanisms to, potentially, violent Strombolian mechanisms. Cone growth was accompanied, and sometimes disrupted, by effusion of lavas from the bases of cones. Pyroclastic cones were built upon a gently southward-sloping surface and were prone to failure of their down-slope (southern) flanks. Early lavas flowed primarily southward and, at Red and Black Cone volcanoes, carried abundant rafts of cone material on the tops of the flows. These resulting early lava fields eventually built platforms such that later flows erupted from the eastern (at Red Cone) and northern (at Black Cone) bases of the cones. Three major surface features – scoria cones, lava fields with abundant rafts of pyroclastic material, and lava fields with little or no pyroclastic material – experienced different post-eruptive surficial processes.

Contrary to previous interpretations, we argue that the Pleistocene Crater Flat volcanoes are monogenetic, each having formed in a single eruptive episode lasting months to a few years, and with all eruptive products having emanated from the area of the volcanoes' main cones rather than from scattered vents. Geochemical variations within the volcanoes must be interpreted within a monogenetic framework, which implies preservation of magma source heterogeneities through ascent and eruption of the magmas.

**Key words:** Scoria cone, basalt, lava flow, polycyclic, monogenetic, Strombolian, violent Strombolian

## INTRODUCTION

Small volume basaltic volcanoes composed of cones, lava flows, and tephra fallout deposits (total eruptive volumes on the order of  $1 \text{ km}^3$  or less) are among the most common continental volcanic landforms. Three motivating factors for detailed studies of such volcanoes are: (1) Their field characteristics provide important clues about the ascent and eruption of basaltic magma (e.g., McGetchin et al., 1974; Self, 1976; Blackburn et al., 1976; Heiken, 1978; Wood, 1980a; Houghton and Schmincke, 1989; Luhr and Simkin, 1993; Valentine and Groves, 1996; Reidel et al., 2003; Valentine et al., 2005). (2) Although usually limited to areas on the order of tens of square kilometers, the immediate consequences of eruptions at these volcanoes can be quite devastating, endangering property, infrastructure, and air travel (e.g., Luhr and Simkin, 1993; Carn, 2000; Siebert and Carrasco-Núñez, 2002; Dellino and Kyriakopoulos, 2003; Siebe et al., 2004). Cities such as Auckland, New Zealand, and Mexico City are built directly on recently active basaltic volcanic fields and are therefore vulnerable to these hazards (e.g.,

Valentine, 2003). An additional hazard that has motivated studies in the United States is the need to predict the consequences of a small-volume basaltic volcano intersecting a permanent, underground radioactive waste repository at Yucca Mountain, Nevada (Crowe et al., 1983a; Crowe, 1986; Doubik and Hill, 1999; Woods et al., 2002; Darteville and Valentine, 2005). (3) A combined understanding of the ages of individual volcanoes, their original surface characteristics, and modern surficial features provides important information on the types and rates of geomorphic processes in a given climatic setting (e.g., Wood, 1980b; Wells et al., 1985; McFadden et al., 1987; Hooper and Sheridan, 1998; Valentine and Harrington, submitted).

In this paper we describe the physical volcanological aspects of five Pleistocene basaltic volcanoes in Crater Flat basin, southern Nevada. While any tephra fallout deposits that might have been associated with the volcanoes are largely obscured, many original volcanic features are preserved and in some places erosion has exposed important features in the interiors of the cones and lavas. These features, combined with the modern surface characteristics, provide important insight into the emplacement of the cone-forming deposits and lavas and into their geomorphic evolution in arid settings.

## **BACKGROUND**

Crater Flat (Figure 1) is an alluvial basin in the Basin-and-Range province of the western United States. It is bounded to the east by ridges of tilted Miocene ignimbrites (Yucca Mountain) and to the west by uplifted Paleozoic sediments (Bare Mountain). Basaltic volcanism within the basin has occurred in three cycles. The first cycle, between 10-11.5 Ma, produced widespread basalt flows that are now mostly buried by alluvium

but have been penetrated at various depths by drilling in the central and northern parts of the basin, and are exposed in hills that form the southern boundary of Crater Flat (Stamatakis et al., 1997; Perry et al., 1998). The second cycle occurred in the southeastern quadrant of the basin about 3.7 Ma (Fleck et al., 1996; Perry et al., 1998). This cycle erupted along a north-south trending fissure system and formed a low shield-like accumulation of lavas and spatter cones; it was subsequently disrupted by normal faults into 4-5 blocks that are now gently tilted to the east and partly buried by sediments. The third cycle, which produced the volcanoes that are the focus of this paper, occurred around 1 Ma (Fleck et al., 1996; Perry et al., 1998; Bechtel SAIC Company, 2004a) to form a NE-trending arc of five volcanoes – SW and NE Little Cones, Red Cone, Black Cone, and Makani volcanoes (Figure 1. *Note* – Makani volcano is also referred to as “Makani Cone,” “Northern Cone” and “Northernmost Cone” in the literature). The Lathrop Wells volcano, located about 5 km outside the southeast margin of Crater Flat, erupted ~80 ka (Heizler et al., 1999). This volcano has been the subject of physical volcanological and geomorphic studies that are reported elsewhere (e.g., Crowe et al., 1983a; Wells et al., 1990; Bechtel SAIC Company, 2004b; Valentine et al., 2005; Valentine and Harrington, submitted).

Vaniman et al. (1982) described the geochemical and petrologic characteristics of the 1 My volcanic centers. The eruptive products are sparsely porphyritic and are alkali basaltic to hawaiitic (trachybasaltic) in composition (see also Vaniman and Crowe, 1981; Bradshaw and Smith, 1994; Fleck et al., 1996; and Perry et al., 1998). Olivine is the principle phenocryst, with rare amphibole (mainly at Little Cones). Nicholis and Rutherford (2004) conducted experiments to determine phase equilibria and ascent rates



for magma from SW Little Cone and Lathrop Wells volcanoes. They determined that SW Little Cone magma erupted at temperatures less than 975 °C with a source pressure of at least 175 MPa (depth greater than ~7 km). Dissolved water content at depth must have been at least 3 wt% for amphibole to crystallize. Comparison of textures between natural samples and those subject to experimental decompression, combined with a lack of plagioclase phenocrysts, suggest average ascent rates of at least 4 cm/s. Melt inclusions analyzed by Nicholis and Rutherford (2004) yielded H<sub>2</sub>O contents mainly in the range of 1.2-1.7 wt% and as high as 3.5 wt% in one inclusion. Luhr and Housh (2002) report values of 1.9-4.6 wt% H<sub>2</sub>O and CO<sub>2</sub> contents up to 930 ppm from Red Cone and Lathrop Wells volcanoes. In summary, the volcanoes discussed in this paper were produced by magmas that were relatively cool (compared to other basalts) and volatile rich, assuming that the above results are representative of all five of the Pleistocene centers in Crater Flat.

The total eruptive volume of the Pleistocene volcanic centers in Crater Flat is 0.14 km<sup>3</sup> (Table 1). Of this, about 0.12 km<sup>3</sup> are accounted for by Red Cone and Black Cone volcanoes; these two receive the most attention in this paper. Note that these estimated volumes account only for the constructional volcanic features that are exposed and/or preserved today (in the case of the two Little Cone volcanoes, this includes lava fields that are buried by alluvium but that are defined by magnetic anomalies). Tephra fallout deposits that might have accumulated beyond the cones and lava fields are no longer preserved, but probably added to the original volume of the volcanoes. By comparison, the combined volume of the lava fields and cone (comparable to the features counted in the volume estimates of the Crater Flat volcanoes) of the ~80 ka Lathrop Wells volcano

is  $0.05 \text{ km}^3$ , which is similar to the individual volumes of Red and Black Cone volcanoes. The tephra fallout deposits at Lathrop Wells account for an additional  $0.04 \text{ km}^3$  for that volcano (Bechtel SAIC Company, 2004b; Valentine et al., 2005).

Two published reports (Vaniman and Crowe, 1981; Bradshaw and Smith, 1994) describe the physical volcanology and eruptive sequences of the 1-Ma volcanoes in Crater Flat, in addition to very brief descriptions in several reports for the U.S. Department of Energy's Yucca Mountain Project (summarized in Perry et al., 1998). Vaniman and Crowe (1981) and Bradshaw and Smith (1994) focus on Red Cone and Black Cone volcanoes. Both papers describe the main cone at each volcano, and the fact that the upper parts of the cones are characterized by coarse, variably welded agglutinate. The papers also describe the presence of two or more lava flows at the volcanoes and mounds of relatively coarse pyroclastic debris scattered amongst the lava flows. However, the interpretations presented by the authors are quite different. Vaniman and Crowe (1981) inferred that the pyroclast mounds record an early phase of pyroclastic eruptions from small, scattered vents. They suggested that pyroclastic eruptions eventually focused at one vent that grew to become the main cone at each center (Red Cone and Black Cone, *sensu stricto*). Lavas filled in around the earlier vents so that they are now preserved as "islands" among the flows.

Bradshaw and Smith (1994) focused mainly on the geochemical evolution of Red and Black Cone volcanoes, but their interpretations of field relations in terms of relative ages of various features were key to their conclusions. Bradshaw and Smith (1994) also inferred that the mounds of pyroclastic debris are individual vents (up to thirteen vents at Red Cone and nine at Black Cone volcano, not counting the main cone at each of those

centers; see Figure 1 of Bradshaw and Smith, 1994), providing partial evidence of a polycyclic history of the volcanoes (i.e., separate eruptions separated by periods of time on the order of  $10^3$  years or more). Other evidence that they called upon to bolster the polycyclic model includes: (1) a feature interpreted to be a feeder dike extending above a lava flow at Red Cone; (2) different morphologies of the two main lava flows at each volcano, primarily in the degree of gullying, distinctness of flow margins, and relief of the lava surfaces (presumably referring to the distinctness and steepness of the flow margins); and (3) an angular unconformity between scoria beds with an associated caliche layer in the Black Cone. Thus, Vaniman and Crowe (1981) and Bradshaw and Smith (1994) both infer the presence of multiple, scattered vents, but came to different conclusions with respect to timing of eruptive events; Vaniman and Crowe assume a monogenetic history (i.e., a single eruptive episode of weeks to years in duration, during which all the features of a volcano are formed), while Bradshaw and Smith promote the polycyclic model.

We present evidence supporting a simpler interpretation of the eruptive processes and sequences at Red Cone and Black Cone, wherein the eruptions at each volcano formed a main cone with lavas emanating from its base within a monogenetic framework that is consistent with historically observed scoria cone-forming events. In addition, we discuss different modes of emplacement of the lavas, effects of lava emplacement processes on the structure of the main cones, and transitions in eruptive style. Similar aspects of Little Cones and Makani Cone are described, although these are much simpler than the two largest volcanoes.

## TERMINOLOGY

The formal names of the eruptive centers include the word *cone* (e.g., Red Cone), and we modify these with the word *volcano* to refer to the combination of lavas and pyroclastic materials and their associated landforms for an eruptive center. The word *cone* is restricted to that specific landform. We use the term *lava flow field* (or *lava field*) to indicate an area that is covered with multiple lava flow units emplaced by multiple mechanisms such as stacking of flow units and inflation. This differs somewhat from the term *compound lava*, which we reserve for stacks of flow units (following Walker, 1973; Francis, 1993), but is similar to the use of *compound lava field* by Pinkerton and Sparks (1976) and Duncan et al. (2004). The topographic high formed by accumulation of lavas is referred to as a *lava platform*. *Boca* refers to a vent, typically located at the foot of a scoria cone, that feeds lava flows and has little if any pyroclastic component. Terms to describe pyroclast size and shape (e.g., ash, lapilli, block, bomb) follow definitions in Fisher and Schmincke (1984). Some of the deposits we describe below are welded to various degrees, ranging from *partly welded* (or *sintered*, where clasts are stuck together where they touch, but are not deformed) to *completely* or *densely welded* (clasts have flattened and coalesced to form a lava-like mass that may contain relict clast textures), with *moderately welded* referring to an intermediate state between these two end members. *Agglutinate* refers to coarse (large lapilli to blocks and bombs) deposits that are welded to some degree. The term *primary* refers to deposits or features that are directly caused by volcanic processes, as opposed, for example, to reworked deposits that have been modified or mobilized and subsequently re-deposited by the action of water and/or wind after eruptions ceased (see also Valentine et al., 1998).

We refer to three types of explosive eruptions in this paper. *Strombolian* eruptions are characterized by pulsed or discrete explosions resulting from bursting of gas pockets from a magma column, producing mainly coarse, fluidal clasts with ballistic trajectories near the vent and scoria lapilli on outer slopes (e.g., Vergnolle and Mangan, 2000; Vespermann and Schmincke, 2000). *Violent Strombolian* events (also referred to as “transitional” by Parfitt, 2004) are characterized by rapidly-pulsed or steady eruptions of well-fragmented pyroclasts to form sustained eruption columns from which clasts are deposited by fallout, except for less abundant ballistic bombs (e.g., Valentine, 1998; Arrighi et al., 2001; Valentine et al., 2005). The eruption columns may be on the order of hundreds of meters to a few kilometers in height. *Hydrovolcanic* events are driven by explosive interaction between magma and groundwater or surface water. Such eruptions typically produce clasts with quench surface textures and low vesicularity.

## **RED CONE VOLCANO**

Red Cone volcano (Figure 2) consists of three major features: (1) a cone remnant that rises 87 m above the floor of Crater Flat, (2) a lava flow field that extends to the south and southwest of the cone remnant (the SW lava field), and (3) a lava flow field that extends to the south-southeast of the cone remnant (SE lava field).

### **Cone Remnant**

The topographically highest part of Red Cone volcano is a roughly horseshoe-shaped remnant of *in situ* cone deposits (Figure 3A) that exposes two main pyroclastic facies. Xenoliths are extremely rare in both of these facies – we observed only a few cm-sized xenoliths, probably derived from basin fill sediments, in the entire cone remnant.

Deposits on the west and northern parts of the cone remnant are mainly lapilli and small blocks, are clast supported, form crudely-defined massive beds, and are partly welded to the extent that clasts retain their original shapes but are sintered together where they touch – these deposits form the *lapilli-and-block facies*. Lapilli are poorly to moderately vesicular with mainly sub-millimeter vesicles and are blocky to subrounded in shape; many of these clasts likely are fragments of larger blocks or bombs that were recycled or churned due to avalanching of crater wall material into the vent and subsequent re-ejection (McGetchin et al., 1974; Heiken, 1978). Blocks (and some bombs) are typically 20-30 cm in size and range from dense with blocky shapes to moderately vesicular clasts with fluidal shapes and cauliflower surface textures (inferred to record surface quenching by water or wet steam; Fisher and Schmincke, 1984). Larger (up to ~50 cm) blocks and cauliflower bombs litter the surface where it is covered by colluvium but were not observed in place; these probably are a lag from eroded cone material.

Bed attitudes in the lapilli-and-block facies on the western part of the cone remnant are irregular but typically dip steeply (50-60°) towards the center of the apparent crater. The deposits are locally faulted into small blocks on the order of a few meters wide that retain the original bedding internally, but that have undergone differing degrees of rotation. At the northwestern summit a small dike, about 10 m long and up to ~30 cm wide, trends northward (probably a radial dike from the vent). On the eastern side of the cone remnant beds of this partly welded lapilli-and-block facies are nearly horizontal in attitude or dip shallowly back into the cone. These are broken into small fault or slump blocks. There is one small exposure, on the east slopes of the cone remnant (Station RC-11, Figure 2B), of primary, non-indurated scoria lapilli with faint bedding that dips about

32° eastward (away from the center of the cone remnant) – this represents primary, *in-situ* material at the angle of repose that was deposited on the outer flanks of the cone during its growth.

A sequence of several meters of coarse lapilli, spatter, and fluidal bombs that forms individual beds ~1 m thick overlies the lapilli-and-block facies on the eastern summit. The beds alternate between partly welded to completely welded where clasts have coalesced to form massive, lava-like beds. These dip about 45° towards the north (strike varies around ~N75°W). We refer to these deposits as the *spatter facies*. The characteristics of this facies require a period of pulsing fountain eruptions where the relatively coarse clasts had a short flight time (minimum cooling) and a rapid accumulation rate (allowing for coalescence and welding of clasts). Deposition was likely very close, within some tens of meters, of a vent (see Head and Wilson, 1989; Sumner et al., 2005).

An apron of material eroded from the cone surrounds the cone remnant, and the apron is in turn deeply rilled (Figure 2A). The apron partly covers the two lava flow fields to the south and east and merges with the Crater Flat valley floor to the west and north.

## **Lava Flow Fields**

### ***Southwest Lava Flow Field***

The SW lava flow field at Red Cone volcano fans out from the cone remnant to form a series of lava terraces that step down toward the distal edge of the flows. The lavas flowed down the gentle (about 20 m/km) south-southeast slope of the Crater Flat valley floor. The length:width ratio is ~1:1 (length measured southward from the cone, width

measured along the widest east-west dimension). There are four main surface features on the lava field: (1) relatively flat areas, (2) flow fronts or margins, (3) lava ridges, and (4) pyroclast mounds. Flat areas have a desert pavement of scoria lapilli (commonly ~1 cm in size, depending upon distance from the cone remnant) with variable quantities of block-size clasts (ranging from surface mosaic types DP-1 to BG-1 as described on a 560 ka lava flow at the Cima volcanic field described by Wood et al., 2002, 2005). The latter are typically angular in shape and are poorly to moderately vesicular. This bimodal grain size characteristic reflects a combination of fallout lapilli and weathered fragments from the original lava surface (e.g., Valentine and Harrington, submitted). Beneath the pavement is a zone (depth unknown, but probably variable) of eolian sand and silt forming a desert soil.

Flow fronts are partly obscured by alluvial deposits of reworked pyroclastic material that form relatively smoothly-sloping surfaces to the surrounding valley floor, but where exposed the fronts are steep, lobate, and comprised largely of lava blocks on the order of decimeters in size. The terrace-like nature of the lava field is especially apparent along its margins, where each flow front forms a step (typically a few m high) downward to the south and southwest.

Lava ridges are typically arcuate in shape (although some are roughly equant in map view, possibly representing tumuli), range from ~5-50 m in length, are a few decimeters to ~2 m wide, and rise up to 2 m above the surrounding surface. Internal textures in these ridges are dominantly nonvesicular to moderately vesicular, massive to platy-jointed lava. Although the ridges occur in a scattered fashion throughout the lava field, they are most abundant near flow margins (see Figure 3B) where they appear to be



squeeze-up ridges, roughly parallel to the flow margin, caused by pulses of lava behind a slowing flow front. This interpretation is supported by observations where gullies have exposed flow interiors within about 200 m of the southern margin of the SW lava field. The flow interiors contain foliation patterns (due to vesicle concentrations or slide planes in the plastically-flowing lavas) that range from horizontal to upward-sweeping; these record ramping and squeezing up of lava near flow margins that is expressed on the surface by the lava ridges. Depending upon the degree of erosion, the lava ridges can be similar in appearance to exposed dikes – in a sense they are “rootless” dikes since they are fed by the underlying lava flow rather than by a deeper magma reservoir. Two additional lava ridge features occur on the leading (southern) edges of pyroclast mounds (see below). These are also arcuate and parallel the contours of their host mounds, and resemble dikes.

There are several mounds of pyroclastic debris, ranging from a few tens to ~200 m in basal diameter, that rise 5-10 m above the SW lava field surface (e.g., Figure 3D). The mounds have subdued, rounded surfaces and are littered to varying degrees with scoria lapilli, blocks, and bombs with eolian sand between the pyroclasts. In most cases the tops of the mounds have the coarsest clasts, probably representing lag deposits, while smaller lapilli have been moved down the shallow slopes by surficial processes. Coarse clasts have a wide range of vesicularity and a range of surface textures including ropy, fluidal textures (e.g., spindle bombs or bomb fragments) to blocky, although wind erosion has smoothed some features. Some large blocks are composed of agglutinate or basalt breccia. Bradshaw and Smith (1994, p.168) state that at Red Cone volcano “cinder mounds typically occur at the tail-end of individual flows, and thus represent actual vent

sites.” However, because post-eruptive surficial processes have obscured many original lava features, we were not able to distinguish individual flows (in the sense of flow units) except perhaps as individual lobes at the distal margin of the lava field. Additionally, we observed pyroclast mounds out to the margin of the SW lava flow field, along its eastern side, and Bradshaw and Smith (1994) also mapped these. Bradshaw and Smith (1994, their Figure 1) mapped several features in the mounds as “intrusives” into the pyroclast mounds of the SW lava field, supporting their hypothesis that the mounds are actual satellitic vents. We note that the largest of these are elongate and are parallel and just inboard from the flow edge – the same setting as squeeze-up lava ridges described in the previous paragraph.

The abundance of large pyroclast mounds on the SW lava field promoted development of gullies in the topographic lows between mounds, that now branch as rills onto the lower slopes of the mounds and have merged downstream with headward-eroding gullies that nucleated between marginal lava lobes. This drainage system supplies pyroclastic debris to the alluvial slopes that obscure some of the flow-margin features of the SW lava field, and has locally incised the distal portions of the lava field to expose flow interiors, as mentioned above.

### ***Southeast Lava Flow Field***

The SE lava field spreads from the eastern base of the cone and extends southward (Figure 2) and has a length:width ratio of ~2:1 (flow length is measured north to south, in the dominant direction of flow). It appears to overlap the SW lava field where the two flows’ margins come together at the apex of a small canyon that is the gap between the eastern and western margins of the two lava fields. The fact that the flows

that fed the SE lava field first flowed eastward is also consistent with the SW lava field being emplaced first and forming a topographic high that diverted subsequent lavas. The top of the SE lava field is relatively flat compared to the SW lava field and locally is covered with a pavement dominated by lapilli-sized scoria with some small blocks (similar to surface mosaic type DP-1 of Wood et al., 2002, 2005), and eolian material beneath the pavement. The few pyroclast mounds that occur on the SE lava field rise only a few meters above the surroundings and tend to have flat tops that are armored with very mature desert pavements (see above; Valentine and Harrington, submitted), although one or two small mounds, which are dominated by block-sized fragments of fluidal bombs, do have rounded tops.

The margins of the SE lava field are lobate in form and very steep, descending 25-30 m to the valley floor. Lobes have typical horizontal dimensions of about 40-100 m and many have top surfaces that step down as terraces, each several meters high, toward their distal ends. We infer that the down-stepping terraces represent small lava breakouts from the toes of lobes (see also Pinkerton and Sparks, 1976), each reaching successively farther onto the desert floor. Similar to the lava lobes described for the SW lava field, the surfaces of those on the edge of the SE lava field are characterized by decimeter-sized lava blocks; a feature that is shared by all of the Pleistocene lava flow fields in Crater Flat is the common occurrence of arcuate lava ridges, parallel to and just inboard from the flow margins.

Drainage networks are less strongly developed on the SE compared to the SW lava field. This is likely due to the lesser initial topographic variation and less abundant pyroclastic debris on the SE lava field. Drainage development has been more restricted

to headward erosion of gullies that nucleated between lava lobes at the margin of the lava field.

### **Interpretation and Summary of Red Cone Volcano**

The two pyroclastic facies in the cone record two principal cone-building eruptive mechanisms. The lapilli-and-block facies represents accumulation of primarily solidified and well-fragmented clasts even in very proximal locations. While the clasts were hot enough to sinter and form an indurated deposit in the crater, they were sufficiently cool to retain their blocky shapes. It is possible that this facies formed during periods of violent Strombolian eruption that alternated with steam explosions that ejected little juvenile material but that re-ejected previously-erupted clasts (and block/bomb fragments) that had slumped into the vent. Some of the internal faulting and rotation within the lapilli-and-block facies may be due to slumping of deposits as cone material was rafted away on top of lava flows (discussed below), in addition to a potential component of slumping during post-eruptive cone degradation. The spatter facies records more “classical” Strombolian eruptions (see, e.g., Valentine and Groves, 1996; Valentine et al., 2005). Each densely welded zone in this facies formed during a peak in the clast accumulation rate for a given Strombolian burst. Lack of exposure prevents direct observation of cone facies that may underlie the lapilli-and-block facies, and it is unclear whether erosion might have removed deposits above the spatter facies; we do not know how much of the cone’s history has been lost or obscured. It is likely that during much of the eruptive history of Red Cone volcano the cone was horseshoe-shaped (open to the south) in map view due to the large amount of cone material that was rafted away atop the SW lava field.

Although both Vaniman and Crowe (1981) and Bradshaw and Smith (1994) inferred that pyroclast mounds scattered throughout the lava flow fields (particularly the SW lava field at Red Cone volcano) are remnants of vents, we favor an interpretation whereby these mounds are comprised of proximal pyroclastic material rafted from the main cone (see also descriptions of rafted cone material at other small volume basaltic volcanoes; Gutmann, 1979; Holm, 1987; Luhr and Simkin, 1993). Although interpretation of these features is complicated by the degree of post-eruptive surface modification, we argue that this interpretation is consistent with several observations: (1) The tops of the coarse pyroclast mounds are rounded and preserve no evidence of an eruptive vent or crater. (2) The mounds cannot be linked to individual lava flow units and occur out to the distal margins of lavas. (3) Features in the main cone suggest that its crater opened to the south and that deposits in the cone may have experienced syn-eruptive slumping as would happen if the cone was undermined as material rafted from its base. (4) Lava ridges or dike-like features on the inferred leading edge of some scoria mounds are very similar to lava squeeze-ups at the front of rafted "mesoblocks" on the 1986 lavas at Izu-Oshima Volcano, Japan (Sumner, 1998). The squeeze-up features at Izu-Oshima resulted as lava from the fluid interior of the flow extruded through cracks in the chilled lava surface because of the weight of the rafted material and deceleration of lava behind a slowing flow front. An additional piece of evidence that occurs at Black Cone volcano (discussed below) is an exposure of the internal structure of a pyroclast mound showing that it consists of steeply-tilted layers of scoria and spatter (similar to rafted cone material on lavas associated with the ~1ka Sunset Crater volcano, Arizona; Holm, 1987).

Sumner's (1998) description of squeeze-ups at Izu-Oshima, which also occur near flow margins, details how the tops of the features in some cases have an outward-flaring structure caused by the plastic behavior of the rapidly-cooling lava as it protrudes above the flow surface. We have observed very similar squeeze up features in lava lobes in the much younger, but compositionally similar, Lathrop Wells volcano (Figure 3E), and Duncan et al. (2004) describe the active development of such squeeze ups at Mount Etna, Italy. Bradshaw and Smith (1994, p. 168) interpreted such a feature where it occurs along the eastern margin of the SW lava field as follows (at Station RC-5, see Figure 2B): "Flow foliations and vesiculation in the top of one of the dike (*sic*) units suggests a mushroom-like shape that might be expected as a lava reaches the surface and initiates a new flow" (note – there is no evidence for a presumed flow that was fed by the dike). It seems likely that this feature is a lava squeeze-up (a rootless dike) from the core of the underlying flow, rather than a true dike related to a separate magmatic (polycyclic) event. Gutmann (1979) describes similar features where lava squeeze ups intrude overlying pyroclastic deposits produced later in the eruption sequence of the same vent in the Pinacate volcanic field.

With the above in mind, we suggest that as Red Cone grew, it was simultaneously cannibalized by lavas flowing from its southern perimeter that rafted away segments of cone material (similar to processes witnessed at Parícutin volcano, Mexico; see Luhr and Simkin, 1993). The rafted material was coarse-grained, rich in bombs and bomb fragments due to its origin close to the vent. Individual rafts may have retained their original bedding structures (Holm, 1987), particularly if there was any welding or agglutination, or in other cases may have been piles of unstructured, loose debris;

however, subsequent surficial processes have obscured differences between these features. Lava squeeze-ups formed on the leading edges of at least two rafts, as well as intruding the bottoms of rafts that were transported to the flow margins. This early phase of lava flows produced the SW lava field through a combination of stacking of flow units and inflation by successive injections of lava (as at Parícutin; Luhr and Simkin, 1993). Eventually the SW lava field became thick enough to divert subsequent lavas such that they initially flowed eastward until they cleared the SW lava platform, at which point they turned and flowed southward down the slope of the valley floor. These later flows accumulated to form the SE lava field. The SE lava field rafted much less material from the main cone, perhaps due to better stability or strength of the cone in the area of the SE flow vent (discussed later), or because production of pyroclasts at the vent had waned or completely stopped during the SE flows. The presence of patches of desert pavement formed by well-sorted scoria lapilli suggests that some fallout accumulated on this lava field either during or after its emplacement.

After eruptions ceased, surficial processes gradually began to degrade the main cone. Rilling and down slope transport of cone deposits produced an apron of reworked scoria lapilli and blocks. The apron was in turn subject to rilling and a second generation of down slope transport that is in process today. The cone erosion processes were likely intimately tied to pedogenic processes that introduced eolian sand and silt and eventually calcium carbonate zones in the upper tens of centimeters of a volcanic deposit in this arid to semi-arid environment (Wells et al., 1985; McFadden et al., 1987; Valentine and Harrington, submitted). The erosional processes act to give the cone a concave-upward profile characteristic of highly degraded scoria cones (e.g., Wood, 1980b; Wells et al.,

1990; Hooper and Sheridan, 1998), although we note that at least on its southern side the cone may have had an *initial* concave profile due to the large quantity of material rafted away on the SW lava field.

The surfaces of the two lava fields evolved in somewhat different manners. The SW lava field, with its abundance of pyroclast mounds, had a combination of relief and loose debris that promoted relatively faster and more extensive development of drainage networks and alluvial aprons or “fans” at the mouths of gullies. Where the SW lava field did not have pyroclast mounds on its top, its surface evolution involved the gradual smoothing of the rough lava surface by eolian deposition in low spots and by weathering of high features (see Wells et al., 1985). The SE lava field, on the other hand, had much less initial topographic variation and less loose debris on its surface, and simply has undergone gradual smoothing with associated soil and desert pavement development such that it now forms a relatively flat-topped platform. Both the SE lava field and the flat parts of the SW lava field are currently at Stage B in the surface modification scheme of Wells et al. (1985). Some drainage network development has occurred on the surface of the SE lava field where there are three subdued mounds, but for the most part its erosion is dominated by very slow headward erosion of gullies between marginal lava lobes. Because there is relatively little transport of loose debris from the central parts of the SE lava field, there is substantially less accumulation of alluvial fans or aprons that would obscure or smooth the edge of the lava field. Thus we infer that the differences in modern morphology between the two lava fields is a result of the different starting morphology and surface materials, which is in turn related to variations in eruptive and emplacement processes.



## BLACK CONE VOLCANO

Black Cone volcano (Figure 4) shares many of the characteristics of Red Cone, including the presence of a single main cone, rising 118 m above the surrounding desert floor, and two (possibly three) lava flow fields (see also Bradshaw and Smith, 1994), the first of which flowed south from the cone and has many pyroclast mounds (S lava flow field), and the second of which spread around the northern base of the cone (N lava flow field). We focus here on features that are unique to Black Cone and refer to the previous section for features that are shared with Red Cone.

### Cone Remnant

Although Black Cone proper at first glance appears to be relatively complete cone, nearly all the *in situ* primary pyroclastic deposits that crop out on the cone are inward-dipping. This implies that a large volume of cone material that formed outward-dipping deposits has been removed by erosion. Most of the surface of the cone is covered with colluvium that has been indurated by pedogenic carbonate build-up, but exposures of primary volcanic deposits indicate that there are two main pyroclastic facies (Figure 5A). The predominant one, which occupies the lower ~80% of the cone, is composed mainly of coarse scoria lapilli and fluidal bombs and forms the *lapilli-and-bomb* facies (Figure 5B). Bedding in this facies ranges from massive, to crudely defined by bomb horizons, to lenticular and inversely graded grain avalanche beds; dips are typically 25-30° into the cone. Scoria lapilli are moderately vesicular and are predominantly blocky and angular in shape. The clast-supported framework of lapilli, which is nonwelded to slightly sintered, contains variable portions of larger bombs. The

bombs are most commonly a few decimeters in length (parallel to crude bedding) and around one decimeter thick, although some ribbon bombs are as long as 1.4 m and rare ovoid bombs are over 2 m in diameter. Many bombs enclose blocky scoria lapilli (accretionary bombs; Heiken, 1978), likely caused as fluid bombs landed on the scoriaceous slopes, enfolded scoria as they rolled or slumped back into the vent to be re-ejected or simply as they rolled or slid into their final resting places. Dense blocks of several decimeters size also occur in this facies but are less common than bombs; otherwise, the facies is similar to the lapilli-and-block facies that forms the lower parts of the Red Cone remnant.

The upper ~20% of Black Cone is dominated by alternating zones of partly to densely welded spatter (Figure 5C), forming a spatter facies that is similar to that at the top of Red Cone. We note that the transition from lapilli-and-bomb to spatter facies may be a lateral transition instead of, or in addition to, a vertical transition; stratigraphically lower deposits that we observed are also farther away from the central vent area due to the slopes of the cone remnant. Thicknesses of ledge-forming welded horizons range from one spatter clast thickness (~10 cm) to about 2 m. Thicker beds, which also have the densest welding, tend to grade laterally over distances of 20-30 m to less welded zones with poorly-defined bedding. The gradation typically occurs as a gradual thinning of the densely welded middle zone of a layer, increasing distinctness of clast outlines, and increasing abundance of lapilli relative to spatter and bombs. These features record deposition from asymmetric, short-lived spatter fountains. Locally the thicker densely welded zones have swirling textures indicative of some rheomorphic flow (a.k.a. rootless or clastogenic lavas). The spatter facies bedding dips concentrically inward toward the

center of a ~75 m diameter, bowl-shaped crater at the summit of Black Cone. Gullying on the southwest side of the crater has exposed deposits relatively close to its low point, and these are dominated by a 4 m thick bed of densely welded spatter (Figure 5D) that grades laterally over 10-20 m into a less welded zone in a manner similar to that described above. Previous authors (Vaniman and Crowe, 1981; Bradshaw and Smith, 1994) have referred to this as a lava lake. However, a lava lake would normally be expected to have a bottom contact that conforms to the crater walls and floor, a flat top, and a relatively massive interior throughout its extent. Strictly speaking, this feature near the summit of Black Cone is simply another local, densely welded spatter zone rather than a true lava lake.

Crustal xenoliths are rare at Black Cone, but there is a horizon in the spatter facies that contains relatively abundant (estimated at a few percent by volume), white, vesiculated xenoliths with margins that indicate potential melting into the basalt host. These xenoliths are probably derived from the alluvial sediments that fill Crater Flat basin. Their presence in deposits that were produced by dominantly magmatic (Strombolian) eruptions (see below) underscores a point made by Valentine and Groves (1996), namely, that shallow crustal xenoliths do not necessarily record a locus of hydrovolcanic explosions in the volcanic feeder system.

We located only two places where the angular unconformity that forms the contact between crater filling (inward dipping) and cone slope forming (outward dipping) deposits is exposed; both of these only occur in the lapilli-and-bomb facies (see Figure 4B, Stations BC-9, 10). These limited exposures and the patterns of bed orientations suggest that the cone may have had a crater that was open to the south-southeast during

early phases (also consistent with rafting of cone material atop early lavas, discussed below), but that subsequently healed so that its final phases (assuming the current top of the cone is close to the height of the crater bottom at the end of eruptions) formed the relatively simple, circular crater that is indicated by the inward-dipping beds of the spatter facies at the summit of the cone remnant. However, as with Red Cone, we do not know how much of Black Cone's original mass has been removed or obscured by erosion. Bradshaw and Smith (1994, p. 168) allude to the presence of a caliche layer along one of the angular unconformities, but do not provide a location. The only feature that we were able to find that resembles such a caliche layer is a layer of coarse ash along an unconformity that appears to have high calcium carbonate content (Figure 4B, Station BC-9). However, this is due to pedogenic processes on the modern surface, where carbonate accumulation can vary as a function of the host material grain size. Larger scoria lapilli in the surrounding exposures are commonly coated with white carbonate, especially on their undersides, that is left after the evaporation of infiltrated rain water, while ash layers tend to hold water in the pores between clasts until the water evaporates, leaving carbonate material that is evenly distributed throughout the deposit. Thus the "caliche layer" does not record a significant (polycyclic) time break. The angular unconformity is simply one that is so commonly associated with scoria cone construction, with inner and outer slopes, periods of slumping and healing, and changes in geometry (e.g., McGetchin et al., 1974).

The cone remnant has a concave upward profile in most quadrants, is deeply rilled on its flanks and is surrounded by an apron of reworked pyroclastic debris that is also rilled. A gully system that cuts into the southwest flanks of the cone remnant exposes

some scoria and bomb deposits near the base of the cone with poorly defined bedding that appears to dip shallowly (10-20°) away (southward) from the cone. It is not clear whether these are primary deposits from early cone-building or if they are part of the reworked apron material. Because the true base of the cone is likely buried beneath ~20-30 m of lava, it seems the latter is most likely.

## **Lava Flow Fields**

### ***South Lava Flow Field***

The S lava field consists of a relatively low-lying, flat-topped area on its eastern part (possibly a lava field from a separate phase of eruptions, but not further distinguished here; Figure 4B) and a larger area that has several large pyroclast mounds. Then length:width ratio is ~1:2. In general the pyroclast mounds are similar to the mounds on the SW lava field at Red Cone volcano. Most have shallow slopes and gently rounded tops that are littered with coarse (in some cases meter-sized) fluidal bomb fragments, scoria lapilli, and blocks. One mound has a beveled top that is littered with relatively dense lava blocks scattered among a “matrix” of large scoria lapilli – this mound may have originated as a high lava surface (e.g., a tumulus) that was covered with fallout scoria, rather than being a more easily modified mound of pyroclastic debris. A mound near the eastern part of the S lava flow field (Figure 4B, Station BC-13) is littered with blocks and boulders of moderately welded agglutinate. Some of the larger blocks retain crude internal bedding, but there is no systematic orientation from one block to another. This is consistent with an origin by rafting of proximal pyroclastic facies from the main cone, and disintegration of the material as it was carried atop a lava flow, rather than the mound being a vent in which bedding orientations should vary systematically

around the mound. In common with the SW lava field at Red Cone, the S lava field at Black Cone volcano flowed from the base of the cone southward along the gentle slope of Crater Flat.

Post-eruptive surface features on the S lava field are also similar to the SW lava field at Red Cone. Gullies formed in topographic lows between pyroclast mounds on the interior parts, and between flow lobes at the margin, of the lava field. In some places the gullies have exposed interior features of pyroclast mounds. One excellent example (Figure 4B, Station BC-14, and Figure 6A) exposes steeply tilted ( $\sim 80^\circ$  northward toward the main cone) beds similar to those found in the main cone remnant, consistent with an origin of the mound by rafting of cone material where original bedding was preserved but rotated and tilted as it traveled atop a lava flow (e.g., Holm, 1987; Sumner, 1998). Rills branch from the main gullies up onto the flanks of scoria mounds, and this drainage network in turn delivers pyroclastic debris from the interior of the lava field to its margins where it is actively accumulating as small alluvial fans or aprons that obscure the marginal features of the lava field.

### ***North Lava Flow Field***

Accumulation of the early S lava field essentially blocked the pre-eruptive topographic gradient of the Crater Flat valley floor around Black Cone such that subsequent lavas vented from the N-NE base of Black Cone (probably from one or more bocas that are now buried by the reworked scoria apron) and spread in a fan-like manner around the northern half of the cone. The N lava field's length:width ratio is  $\sim 1:2$ , similar to that of the S lava field. A range of flow structures can be distinguished, even though the surface of the lavas has been modified. These include both arcuate lava ridges

and circular or equant blisters or tumuli (Figures 6B,C) that appear to be due to squeeze-up processes in the active flows.

The N lava field forms a thicker platform than the S lava field and several features provide clues to its complex emplacement processes. Broad terraces - each a few meters high and with steep, arcuate margins covered with basalt blocks (flow edges) - on the top of the lava field may record stacking of lava flows along channel areas. Stacking can result if a time interval between lava pulses is sufficient to solidify channel-filling lava so that later pulses flow on top of it (e.g., Kilburn and Lopes, 1991), and by channel overflows (perhaps as described by Rossi, 1997), as may occur if lava flux exceeds the local carrying capacity of a channel. In one location (~700-800 m directly north of the summit of Black Cone) a patch of coarse pyroclastic debris inferred to have rafted from the cone is partly overridden by a lava flow unit, also recording stacking as an important mechanism for building up the lava platform.

Lava lobes along the outer margin are commonly 40-100 m long and 20-40 m wide. Top surfaces of most of these lobes step down as terraces to the valley floor (e.g., Figure 6D) representing, as with the lavas at Red Cone volcano, successive breakouts from the toes of the lobes. The fact that these lobes protrude from the main, thick lava platform suggests that a significant portion of lava transport was through a tube network beneath the surface, with breakouts along the margins being an important mechanism by which the lava field widened and extended away from its vent area. This in turn implies that some of the thickness of the N lava field may be the result of inflation, as well as stacking of flows, as at Parícutin (Luhr and Simkin, 1993) and Etna (Duncan et al., 2004). In one case a narrow (~10-15 m wide) tongue of lava, with preserved levees on either

side of a narrow central channel, appears to extend about 60 m from a terrace on the top of the lava platform toward the marginal lobes, partly overlapping and draping them. This also suggests a complex combination of subsurface transport within the lava field, breakout, and overlapping of lava flow units. We infer that these mechanisms worked in varying proportions in all the Pleistocene lava fields in Crater Flat, but the N lava field at Black Cone volcano better exhibits emplacement features because it is thicker and higher-standing as a result of its lavas having advanced up slope on the valley floor.

Post-eruptive geomorphic features at the N lava field are similar to those of the SE lava field at Red Cone. Much of the top of the lava field is relatively flat as a result of original low spots having been filled with eolian sediment, and high spots having broken down by mechanical weathering (Stage B of Wells et al., 1985). Desert pavements of lapilli-size clasts are locally developed, but in many areas the surface is dominated by angular (often somewhat smoothed by wind erosion) blocks of lava with eolian sediment and smaller lava clasts between. It is likely that these surfaces never had pyroclastic deposits on them, and the surface clasts are derived directly from lava surface rubble and weathered fragments of lava crags (similar to surface mosaic type BG-1 of Wood et al., 2002, 2005). Surfaces between lava terraces are smooth and variably paved, sloping gently downward toward the next lowest terrace. Although there is some drainage development between marginal lava lobes, most of the interior of the lava field is free of gullies or rills.

### **Interpretation and Summary of Black Cone Volcano**

The overall eruptive sequence of Black Cone volcano is similar to that of Red Cone volcano. Pyroclastic facies in the cone remnant preserve an evolution from



eruption of relatively well-fragmented material that was cool and brittle (except for large bombs) upon deposition even very near to the vent, forming the lapilli-and-bomb facies, to eruption of coarse spatter that was sufficiently hot and accumulated rapidly to form the variably welded spatter facies. The lapilli-and-bomb facies may therefore result from eruptions with sustained, high-standing columns approaching a violent Strombolian mechanism (Valentine et al., 2005), although recycling and breaking-up of large clasts by avalanching in the vent area probably had an important role in producing this facies as well. The spatter facies represents a closing phase of weak, asymmetric bursts or short-lived fountains of lava. The cone may have had an open horseshoe shape during part of its eruptive history that was filled in or healed by later pyroclastic activity that terminated with a bowl-shaped crater where the cone remnant's summit is now.

Early lavas emanated from the southern base of the cone. The lavas spread southward following the gentle slope of the valley floor and rafted significant quantities of cone material with them, probably simultaneous with explosive activity such that the lava field's surface was partly covered with fallout lapilli. As the S lava field thickened and spread laterally (eastward and westward), it reversed the local slope such that the later N lava field flowed northward. The N lava field spread and thickened by a combination of stacking and overlapping of flow units and tongues, and inflation with marginal breakouts. This lava field rafted very little cone material and may have occurred after the most dispersive explosive activity (corresponding to the lapilli-and-block facies of the cone remnant) had ceased, as reflected in the lesser abundance of fallout lapilli on its surface. The spatter facies in the cone may have been contemporaneous with the N lava field.

The three main features of Black Cone volcano (cone remnant, S lava field, N lava field) each had different characteristics due to different eruption/emplacement processes, and have each undergone somewhat different post-eruptive geomorphic evolution. The outward-dipping slopes of the cone have been removed, primarily through development of rills and runoff, to form a reworked apron around the cone remnant. This apron is in turn deeply rilled and its deposits are being gradually remobilized to lower elevations. The S lava flow, with its abundance of rafted cone fragments, had an initially hilly surface covered with loose pyroclastic debris. A combination of gully development in low spots between mounds, rilling of the sides of the mounds, and headward erosion of gullies that nucleated between marginal lava lobes, produced an extensive drainage network and transported much pyroclastic debris to the margins of the lava field. This reworked debris is now accumulating as small alluvial fans and aprons that obscure the original lava margins. The N lava field was relatively flat to begin with. Combined accumulation of eolian sediment and mechanical weathering of crags and small highs have smoothed original lava surface roughness. Fluvial erosion and reworking is mainly limited to gullies that nucleated between marginal flow lobes, and the paucity of easily remobilized pyroclastic debris has left the steep flow margins relatively clearly defined. All of these aspects are similar to Red Cone volcano.

## **LITTLE CONES**

### **Description**

Little Cones consists of two cone remnants – the SW and NE cones - the summits of which are separated by ~380 m (Figure 7). Because of their location at the southern end of Crater Flat, alluvial sediments have buried most of the two lava flow fields associated with these cones, but the extent of the lava fields is known from ground magnetic data (Figure 8; Stamatakos et al., 1997; Connor et al., 1997), and has been further refined with recent high-resolution aeromagnetic data (Perry et al., 2005).

The SW cone remnant rises 24 m above the surrounding desert floor. A small quarry pit at the northwest base of the cone exposes clast-support beds of highly vesicular, coarse, blocky scoria lapilli. The beds dip outward, away from the center of the cone remnant, at about 30°. Many of these beds are lenticular and inversely graded, and the show no evidence of welding. The most likely emplacement mechanism is a combination of fallout from sustained eruption columns with avalanching down the cone flanks. The higher flanks of the cone remnant are littered with scoria lapilli and bombs. Bombs are decimeters up to ~1 m in size and commonly preserve some fluidal textures although some have cauliflower surface textures. The abundance of bombs on the surface could be due to a lag effect as smaller lapilli have been removed by runoff, and might not reflect the original abundance in the eruptive deposits. The cone remnant is deeply rilled and surrounded at its base by an apron of reworked pyroclastic material that is also rilled.

The SW cone's crater is open to the south and its lava field extends primarily in that direction; it is likely that the crater was open to the south during eruption with lavas erupting from the south and southwest base of the cone as indicated by aeromagnetic data (Figure 8). Most of the lava flow field exposure is actually a surface with varying

amounts of scoria lapilli and lava blocks, with eolian sand between the clasts. However, near its east edge small lava ridges, probably representing squeeze-up structures as described above, do protrude above the surface, indicating that the top of the lavas is near the surface (Figure 8). The length:width ratio of this lava field is  $\sim 1:1$ .

The NE cone remnant is 15 m high and forms a hill with no crater. It is littered with scoria lapilli and is rilled. The buried lava flow field from NE Little Cone extends 2 km to the south (length:width ratio of  $\sim 2:1$ ), and its geometry is similar to flows observed at the other Pleistocene Crater Flat volcanoes as well as at the younger Lathrop Wells volcano. It is possible that the lack of a crater remnant at NE Little Cone reflects advanced degradation of the cone by rafting of material on top of the lava flows, or simply by post-eruptive erosion. However, since the surrounding alluvial surface is aggrading, and therefore base level for cone degradation is rising, it seems unlikely that post-eruptive erosion at NE Little Cone would have been more rapid than at other Pleistocene volcanoes in the basin.

### **Interpretation and Summary of Little Cones**

In general, Little Cones appear to be similar to Red and Black Cone volcanoes in that they each have a cone that was likely built by a combination of Strombolian and violent Strombolian mechanisms, and lavas that extend southward down the valley slope. However, the Little Cones volcanoes appear to have one lava flow field each, rather than later ones that were diverted around early lavas. Incompatible trace-element compositions of bombs from the two cones differ significantly, consistent with an interpretation that each cone represents a separate eruptive episode. Sr, Th, and La, for example, have

concentrations that are 45-70% higher at SW Little Cone than at NE Little Cone (Perry et al. 1998).

Burial of eruptive features precludes a definitive interpretation of eruptive sequences at these two volcanoes, but the aeromagnetic data combined with the surface exposures south of SW Little Cones allow a reasonable interpretation. We interpret the eastern lava flow field, from NE Little Cone, to represent the younger eruption, because it appears to flow around and past the western lava flow field from SW Little Cones (Figure 8). The SW Little Cones lava flow field appears to have a top that is near the present surface, as suggested by the surface features described above. This implies that the western flow is thicker than the more completely buried eastern flow. The inferred thickness relationship is consistent with the flow shapes indicated by the aeromagnetic data, which suggests a stubby, more viscous western flow from SW Little Cone (possibly reflecting the low temperature determined for SW Little Cone by Nicholis and Rutherford, 2004) and a more fluid, higher effusion rate, eastern flow from NE Little Cone (Figure 8). Stamatakis et al. (1997) used ground magnetic data to model the eastern flow as a 10-meter- thick flow buried by 15 m of alluvium. If this is correct, and if the base of both lava fields is at the same elevation, the thickness of the western flow (which nearly reaches the surface) is about 25 m, similar to flow thicknesses at Red and Black Cone volcanoes. The potential 25 m thickness of this portion of the Little Cones lava fields would result in a small increase in the volume estimate in Table 1.

## **MAKANI VOLCANO**

### **Description**

Makani volcano (also referred to as Makani Cone, or Northern Cone, although these are misnomers because there is no cone structure) is a very small eruptive center that forms a subdued mesa. Its top is ~5 m above the surrounding terrain and the map-view diameter is ~500 m (Figure 9). The eastern half is littered with scoria lapilli and fluidal bomb fragments and eolian sand and silt between clasts, has a slightly rounded top, and has some radiating rills in its surface that supply sediment to a narrow debris apron around the eastern part of the volcano. The western half has a relatively flat surface with lava blocks and eolian sediment between clasts, and a steep western margin of lava lobes.

### **Interpretation**

We interpret Makani volcano to have formed by eruption along a short (200-300 m) , roughly N-S trending fissure. Weak fountaining produced the bombs and scoria and possibly a low profile pyroclastic construct in the eastern part of the volcano, while lavas effused and flowed a short distance westward as aa or blocky flows. Post-eruptive surface processes were dominated by rilling and reworking of loose pyroclastic material on the eastern part of the volcano. The western part is a small lava platform in Stage B of Wells' et al. (1985) surface evolution scheme, and, like the SE lava field at Red Cone and the N lava field at Black Cone volcanoes, has experienced little erosion except for gullies between marginal flow lobes.

## **DISCUSSION**

### **Eruptive and Emplacement Processes**

Explosive activity at the Pleistocene volcanic centers in Crater Flat has been referred to as Strombolian to Hawaiian (e.g., Vaniman and Crowe, 1981; Crowe et al., 1983a,b; Crowe, 1986; Bradshaw and Smith, 1994; Perry et al., 1998) and this inference is commonly made for scoria cones in general. In detail, the explosion mechanisms as indicated by pyroclastic facies are more complex. The volcanoes had phases characterized by Strombolian eruptions *sensu stricto* and by violent Strombolian mechanisms. The facies succession within Red and Black Cone volcanoes suggest that the lower exposures (but not necessarily the lowest deposits, which are not exposed) may record eruption processes toward the violent Strombolian mechanism, while the closing phases of explosive activity were dominated by weak Strombolian bursts. Gutmann (1979) described cones in the Pinacate volcanic field that exhibit upward increases in abundance of coarse blocks and bombs, and capping sequences of welded agglutinate, that appear to be very similar to the sequences we describe. He attributed the variation to an interplay between magma flux and bubble nucleation and growth processes. Previous authors referred to the upper spatter facies at Red and Black Cone volcanoes as deposits of Hawaiian eruptions. However, the alternating degree of welding between beds and the limited lateral extent of densely welded deposits in very proximal locations indicate asymmetric, low, temporally discrete fountains more akin to Strombolian eruptions than to Hawaiian eruptions, which produce sustained lava fountains (e.g., Parfitt, 2004). The presence of cauliflower surface textures on bombs in the lapilli-and-block facies at Red Cone, along with a relatively higher abundance of rounded (recycled) clasts, may reflect a component of magma-water interaction and steam explosions in the vent. Other than

this, and a few cauliflower bombs at SW Little Cone, there is no evidence of any substantial hydrovolcanic activity in the 1-My centers.

All of the volcanoes discussed here, except for Makani volcano, produced lava flows that first erupted from the southern bases of the main cones, and spread south-southwestward down the shallow slope of the Crater Flat valley floor (the estimated southward topographic gradient varies from 25 m/km beneath Black Cone, 20 m/km beneath Red Cone, and 16 m/km beneath the two Little Cone volcanoes). The resulting lava fields at Red Cone, Black Cone, and SW Little Cone volcanoes extend 600-800 m away from their vents, while the lava field at NE Little Cone extends  $\sim 2$  km. The length of NE Little Cone's lava field must reflect a relatively higher effusion rate ( $\sim 1-3 \text{ m}^3/\text{s}$ ) compared to the other volcanoes ( $< 1 \text{ m}^3/\text{s}$ ; Walker, 1973). With these rates the SW and S lava fields at Red and Black Cone volcanoes, respectively, would have been emplaced over periods of 9-12 months.

In detail the flux may have been variable; it may be that for these small lava fields the effusion occurred as discrete pulses that achieved higher effusion rates but for short periods of time. The small length:width ratios for the early lava fields at Red and Black Cones could be explained by a model (Figure 10) where discrete pulses of lava first flowed directly down hill. These flows solidified during a non- or weakly-effusive period, forming a small platform (perhaps a few meters high) that was sufficient, given the gentle paleoslope, to divert the subsequent batch of flows to the side so that over time the field spread laterally as a fan around the south side of a given cone. Lava pulses that were separated by insufficient time for the previous flows to solidify might have inflated those flows, or pushed new extrusions of lava from the toes of marginal lobes. Pulses



that were separated by enough time for previous flows to solidify, but that had low effusion rates, may have traveled across the top of the previously built flows for short distances after which they solidified to form a terrace on the top of the growing platform. Thus a lava field was built in a fan-like manner where the radial distance from the vent to the margin was determined by peak effusion rates of lava pulses, while the circumferential spread was determined by a some minimum period between pulses (sufficient to allow solidification of the just-previous pulse) and the thickness of flow units relative to the slope of the depositional surface. Once the footprint of such a lava fan was covered with flows, stacking and inflation might have continued to thicken the lava field until its top was sufficiently high to essentially reverse the slope around the base of the cone (which was likely to have been growing as all the above was taking place). At this stage, if effusive activity continued, lava broke out from some new location around the base of the cone to form a new lava field (the SE and N lava fields at Red and Black Cone volcanoes, respectively). If effusive activity ceased before this stage the volcano had only one lava field that extended from its downhill side.

The later lava fields at Red and Black Cones grew in different manners. At Red Cone volcano, the SE lava field appears to have welled out of the southeastern base of the cone. After growing a short distance (~400 m) eastward across the paleoslope it was able to catch the southward paleoslope and grow mainly in that direction for a distance of 1.6 km with a lesser degree of lateral spreading, compared to the earlier SW lava field, such that its length:width ratio is about 2:1. In contrast the N lava field at Black Cone appears to have vented from the northern base of the cone. Because its lavas were flowing northward against the paleoslope, individual pulses or flow units were easily diverted

laterally and the resulting length:width ratio is  $\sim 1:2$ . We also infer that a significant component of the N lava field's thickness is due to inflation as lavas were intruded into the interior of the platform as it thickened due to the limited uphill flow capability of the lavas.

We have argued above that pyroclastic mounds observed in association with lavas are not separate vents but are masses of material rafted from the main cones, and a final point with respect to emplacement processes focuses on the fact that these mounds are most abundant on the early lava fields at Red and Black Cone volcanoes, compared to the later lava fields. In our discussion of Red Cone above, we speculated that the later (SE) lava field vented from a stronger part of the cone, or that production of pyroclasts at the vent had waned or completely stopped during emplacement of the SE lava field. The first possibility is related to the observation that the cones were built upon a sloping surface (see schematic cross section views in Figure 10). The downhill (south-southwest) flanks of the cones would be weaker (perhaps in a state of relative tension) than the uphill sides, which were in effect buttressed by the paleosurface. Although the elevation difference between the base of the cones on their uphill and downhill sides would have only been on the order of 10 m, this may have been sufficient to promote cone failure and rafting on lavas emanating from the downhill cone bases. The Lathrop Wells volcano was also formed on a southward-sloping surface and exhibits the same relationships of preferential rafting with its early, southward-emplaced, lava field (Valentine et al., 2005). Gutmann (2002) pointed out that a large number of scoria cones in the Pinacate volcanic field that were built upon a sloping paleosurface are breached on their downhill sides by lavas that carried away significant quantities of cone material as rafts. This suggests that the

process of cone deconstruction by rafting is an important, general process on the development of small basaltic volcanoes that are emplaced upon sloping surfaces.

An issue that cannot be definitively resolved about the Pleistocene Crater Flat volcanoes is whether there were significant fallout tephra deposits that extended beyond the immediate vicinity of the pyroclastic cones. As mentioned in the Background section, the volumes of lava and cone material at Red Cone and Black Cone volcanoes are very similar to the lava and cone volume at Lathrop Wells volcano. Red and Black Cones expose pyroclastic sequences that potentially evolved from early violent Strombolian to late-stage, weak Strombolian eruptions; this is typical of many scoria cones around the world (Wood, 1980a; Gutmann, 1979) but is an opposite trend to that at Lathrop Wells volcano (Valentine et al., 2005). However, because other features of the three volcanoes are very similar it seems reasonable to postulate that Red and Black Cone volcanoes may have originally had laterally extensive fallout deposits similar to that associated with Lathrop Wells ( $\sim 0.04 \text{ km}^3$ ; Bechtel SAIC Company, 2004b). Similarly, the two Little Cones volcanoes may have had laterally extensive fallout deposits but probably not as large as Red and Black Cone volcanoes, assuming that the fallout volume was proportional to cone and lava volumes.

### **Post-Eruptive Surficial Processes**

Different eruptive and emplacement processes at the Pleistocene centers in Crater Flat produced three major surface types: (1) main pyroclastic cone, (2) lava flow fields with abundant rafted cone material, and (3) lava flow fields with little pyroclastic surface material. These three surfaces provided different initial conditions for subsequent

geomorphic evolution, which has been discussed above and is summarized in Figure 11, and add a level of complexity to the landscape evolution scheme of Wells et al. (1985).

Key features of posteruptive evolution of the main cones (Figure 11A) begin with development of rills on cone slopes. Initiation of rilling requires low-permeability areas on the cone surface that enable runoff of rainwaters rather than simple infiltration into loose scoria. At cones that are characterized by closing stages of violent Strombolian activity, such as Lathrop Wells volcano (Valentine et al., 2005; Valentine and Harrington, submitted), a significant period of time, perhaps as much as 100,000 years, may be required as eolian sediment and carbonate clogs pore spaces in loose surface scoria, finally reducing its permeability sufficiently to stop rain infiltration. At the Pleistocene Crater Flat volcanoes, however, the presence of large bombs and densely welded spatter facies from closing pyroclastic eruptions may have provided impermeable surfaces such that runoff and rilling began relatively quickly. Formation and downcutting of rills transports pyroclastic material downward to a growing apron around the base of the cone. As pedogenic processes clog the upper horizon of the reworked apron, it in turn becomes relatively impermeable to rain water such that runoff nucleates and forms rills in the apron, transporting pyroclasts farther away from the cone. This multi-stage process presumably continues until the cone topography is quite subdued.

Lava fields with abundant mounds of pyroclastic material (Figure 11B) develop drainage networks by a combination of headward erosion of gullies that initially nucleate between marginal lava lobes, and development of rills on mound slopes that converge to form gullies in low areas between mounds. The resulting networks transport pyroclastic debris to the distal edges of the lava field, where it accumulates as small alluvial fans and

aprons. These aggradational features obscure the primary features of the lava margins (e.g., flow lobes, steep flow fronts). This contrasts with a lava field that has few or no pyroclast mounds and little or no fallout lapilli on its surface (Figure 11C), which undergoes processes of smoothing on the top of the platform and gullying that begins only between flow lobes at its margin with slow headward erosion. Such a lava field may retain its steep flow fronts and other lava structures much longer than a pyroclast mound-rich lava field. This points out the importance of accounting for different initial conditions of surfaces when determining relative ages based on modern morphology. Bradshaw and Smith (1994) inferred that the different morphologies of the two lava fields each at Red Cone and Black Cone volcanoes represented significant gaps in time between emplacement the lavas (although not specified by Bradshaw and Smith, 1994, such differences would imply time gaps of many 10s-100s of ky), but we argue that the differences primarily reflect different initial characteristics of the lava fields.

Post eruptive surficial processes also provide an explanation for the morphology of pyroclast mounds, most of which have subdued, rounded shapes and abundant coarse pyroclastic material on their tops. There are probably many different types of rafts (e.g., see Gutmann, 1979; Holm, 1987; Luhr and Simkin, 1993); Figure 12 shows post-emplacement evolution of three different types: (1) raft with intact cone bedding (e.g., Holm, 1987), (2) raft of agglutinate deposits that have partly disintegrated during transport on top of a lava, and (3) raft of initially unconsolidated, loose pyroclastic debris blanketed by scoria fallout. These different types of rafts can evolve to mounds with similar appearances that do not on the surface show much of their original character.

#### **Are Red and Black Cone Volcanoes Polycyclic or Monogenetic?**

We conclude that these two volcanoes are monogenetic and that both pyroclastic and effusive products erupted from the area of the main cone. While there were sequences of events that are recorded in the cones as internal unconformities and facies variations, and in the formation of different lava flow fields, it is most likely that these all took place within the framework of monogenetic activity that spanned time scales of months to a few years for each volcanic center (Wood, 1980a). As discussed in this paper, features that Bradshaw and Smith (1994) interpreted as indicators of polycyclic activity (e.g., unconformities within cones, scattered pyroclastic vents preserved as mounds, features they inferred as dikes, and differences in lava field morphology) all can be explained as primary eruptive or emplacement features or as the result of post-eruptive surficial processes acting on different types of surfaces.

Bradshaw and Smith (1994) demonstrated compositional variations, principally in trace elements, between different products of Red Cone volcano, and found that compositions at Black Cone volcano overlap with one end of a spectrum of compositions that occur at Red Cone. The variations cannot be explained by evolution of a single magma batch, but require different or heterogeneous magma sources (Bradshaw and Smith, 1994; Perry et al., 1998). Based upon our work, these geochemical variations need to be considered within a monogenetic framework, rather than a polycyclic framework where magma batches may be separated by sufficient time for the volcanic plumbing system to have cooled from the previous activity. This implies that heterogeneities in the magma source region are preserved through ascent and eruption. Strong and Wolff (2003) discuss possible mechanisms by which basalts derived from

very small degrees of partial melting of heterogeneous sources may ascend to feed different magma batches within a monogenetic eruption sequence.

## CONCLUSIONS

We have shown that the Pleistocene volcanoes in Crater Flat are monogenetic and formed by a range of eruptive processes including Strombolian and, potentially, violent Strombolian explosive activity, as well as development of lava flow fields that thickened by a combination of flow unit stacking and inflation, expanding laterally in a manner determined by an interplay between effusion rates (possibly pulsing) and paleotopography. Cone growth, cone deconstruction by failure of cone segments and rafting atop lava flows, and cone healing were intimately linked and resulted in complex histories preserved in cone remnant deposits. Post-eruptive geomorphic evolution in this arid to semi-arid region was determined by the characteristics of the original volcanic surfaces, thus complicating any relative age determinations based upon erosional characteristics of different volcanic features.

The complex array of eruptive and emplacement mechanisms took place within a framework of monogenetic eruptions, and point to a need for research to determine the controlling factors on changing eruptive processes for basaltic magmas with relatively constant major element compositions. As with other volcanoes, the behavior of these small volume volcanoes must depend upon magma rheology, ascent rate, volatile content, and degassing processes (e.g., Gutmann, 1979; Cervantes and Wallace, 2003; Taddeucci et al., 2004). Given the abundance of small volume basaltic volcanoes in continental

settings, an improved understanding will have implications for both our basic understanding of mafic magmatism and for applications such as volcanic risk assessment.

## **ACKNOWLEDGEMENTS**

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## Figures

Figure 1. Simplified geologic map of Crater Flat and its immediate surroundings (modified from Vaniman and Crowe, 1981). Inset shows location of the study area within the state of Nevada.



Figure 2. Air photo (A) and geologic map (B) of Red Cone volcano.

Figure 3. (A) Cone remnant at Red Cone volcano, viewed from surface of cone apron looking northward. (B) Lava ridge near southern margin of SW lava flow field (Station RC-4), dashed lines indicating foliation. (C) Lava ridge on down-flow flank of a large pyroclast mound (Station RC-12). (D) Photograph taken from slopes of cone remnant looking to the south across the surface of the SW lava field, showing large pyroclast mound in the middle ground. (E) Internal structure of squeeze-up lava feature at Lathrop Wells volcano, a less-eroded equivalent to many lava ridges and dike-like features on the SW lava field at Red Cone, with dashed lines showing foliation.

Figure 4. Air photo (A) and geologic map (B) of Black Cone volcano. Dotted line shows a lava field that is somewhat distinct because of its low profile, but that we have lumped with the S lava flow field in the text.

Figure 5. (A) Photograph of Black Cone (viewed from the south) showing location of lapilli, block, and bomb facies (lower cone), spatter facies (upper cone), upper reaches of debris apron, and location (BC-9,10) of unconformities between outward and inward dipping beds (most exposures are of inward-dipping beds). (B) Lapilli-and-bomb facies characteristic of the lower part of the cone (Station BC-1). Tape is 1 m long. (C) Spatter facies in upper part of cone (left side of photo is toward the vent; Station BC-2). (D)

Densely welded spatter in the upper crater (Station BC-4). Note clast outlines in this otherwise dense lava-like body. Tape is 1 m long.

Figure 6. Features of Black Cone lavas. (A) Interior of pyroclast mound exposed by deep gully along its eastern margin (Station BC-14), showing steeply tilted beds of densely welded spatter (next to hammer) and less-welded agglutinate beds. (B) Arcuate lava ridge that formed as solidified upper part of a lava flow was tilted and pushed upward near the margin of a lava lobe (Station BC-11). (C) Circular lava tumulus in N lava field, ~30 m diameter, located 200 m SE of Station BC-11. (D) Terrace-like down-stepping of a lava lobe toward the valley floor due to successive breakouts (arrows) along eastern edge of N lava field.

Figure 7. Air photo (A) and geologic map (B) of Little Cone volcanoes.

Figure 8. Aeromagnetic anomaly map of Little Cone volcanoes (colors range from blue, representing strong reversed polarity magnetization, to red, which represents strong normal magnetization). Red line shows the extent of surface exposures of primary and reworked volcanic products. Area characterized by high amplitude, small wavelength variations in magnetization are buried lava fields. One lava field spreads south to southwest of SW Little Cone, while another extends about 2 km directly south from NE Little Cone. Asterisks represent centers of cone remnants and triangles are location of lava squeeze-ups. Arrows point to eastern margin of the lava field associated with SW Little Cone.

Figure 9. Air photo (A), and geologic map (B) of Makani volcano.

Figure 10. Sequence of events for developing fan-shaped lava flow fields simultaneously with cone growth on a gently sloping surface. Left column shows cross section view and right column shows map view at corresponding stages. The beginning of the sequence is shown at the top with initial lava flow from a small cone. Subsequent pulses of lava build a fan-shaped lava field. When the thickness of the lava field is sufficient, subsequent lava effusion is diverted to a different location along the cone base (bottom figures).

Figure 11. Schematic illustration of geomorphic evolution of pyroclastic cone (A), lava field with abundant pyroclastic mounds (B), and relatively pyroclast-free lava field (C).

Figure 12. Illustration of post-emplacement evolution of pyroclastic mounds that originate as rafted cone material. (A) Raft emplaced with cone bedding still intact. Gully exposure of tilted beds shown in Figure 6A is an example of this type of mound. (B) Raft of partly welded agglutinate that disintegrated into large blocks during emplacement. Station BC-13 is an example of this type of mound. (C) Raft emplaced as loose, coarse pyroclastic material subsequently covered with fallout lapilli. Note that the top and middle raft types could also be mantled (except on initially steep faces) with fallout lapilli, which would modify their geomorphic evolution somewhat. As time progresses

the initially-different types of pyroclastic mounds grow increasingly similar in appearance due to surficial processes.

TABLE 1 – ESTIMATED VOLUMES OF PLEISTOCENE VOLCANIC CENTERS IN CRATER FLAT

Volcano name	Volume (km <sup>3</sup> ) <sup>†</sup>	Brief description
Black Cone	0.061 <sup>‡</sup>	Single cone with two lava flow fields
Red Cone	0.055	Single cone with two lava flow fields
Little Cones	0.022 <sup>§</sup>	Two small cones, each with a lava flow field (mostly buried by alluvium) extending southward
Makani Cone	0.004 <sup>#</sup>	Small lava field with minor pyroclastics

<sup>†</sup>Volumes calculated by reconstructing a sloping planar paleosurface beneath each volcano (determined by elevation of points around the edge of each volcano, assuming that this is close to the contact between volcanic products and the paleosurface unless noted otherwise), and integrating the digital elevation data above that surface. The volume estimates do not account for distal fallout deposits that may have existed but are now obscured or missing due to post-eruptive surficial processes.

<sup>‡</sup>Bradshaw and Smith (1994) estimate the volume of Black Cone volcano to be  $0.067 \pm 0.015$  km<sup>3</sup>.

<sup>§</sup>Combined volume of SW and NE Little Cone volcanoes and their lava flow fields. Assumes each of the two lava fields is 10 m thick and buried by an average of 10 m of alluvium.

<sup>#</sup>Assumes 5 m partial burial of volcanic products, in addition to those exposed on the surface.

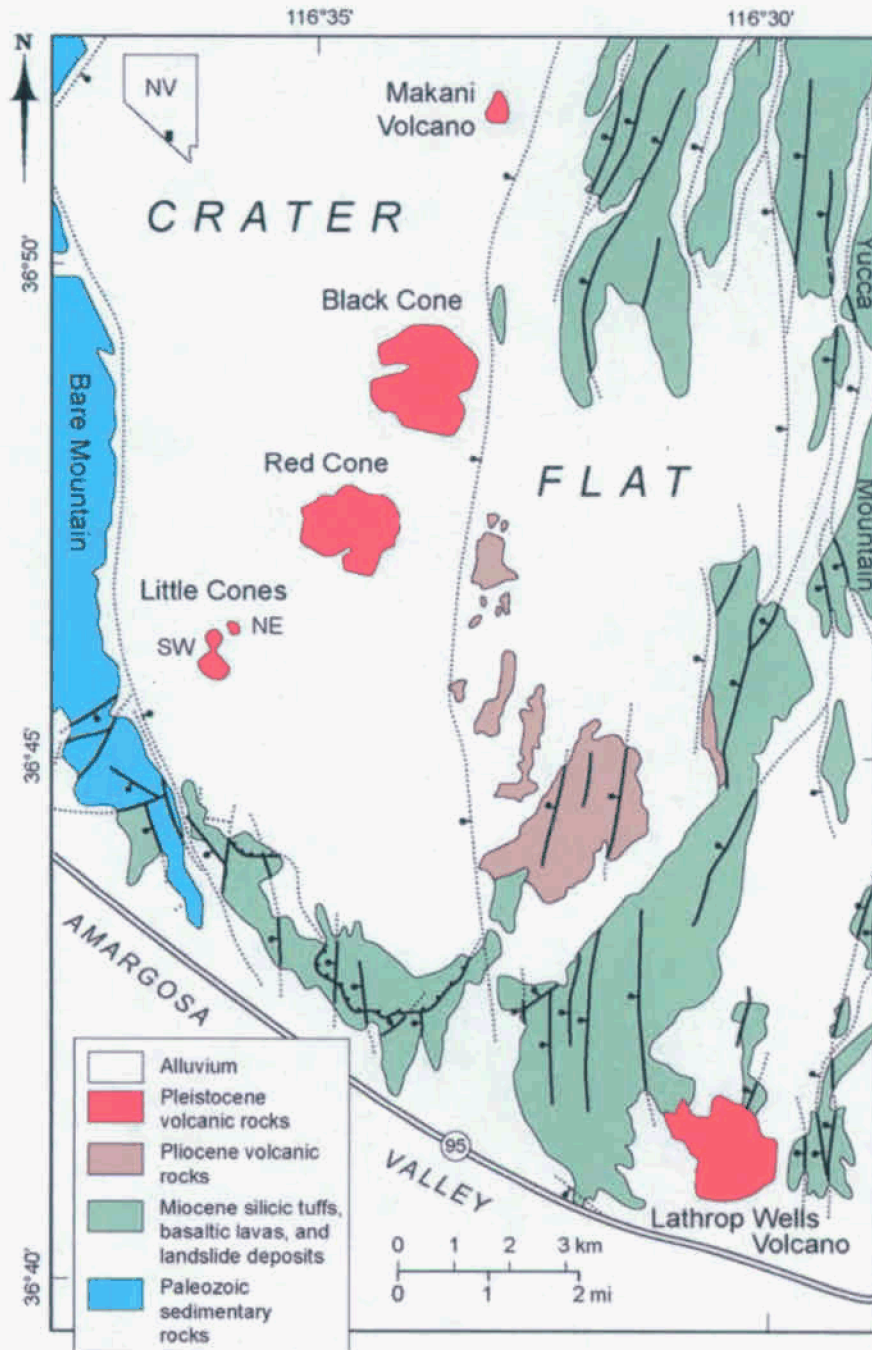


Figure 1

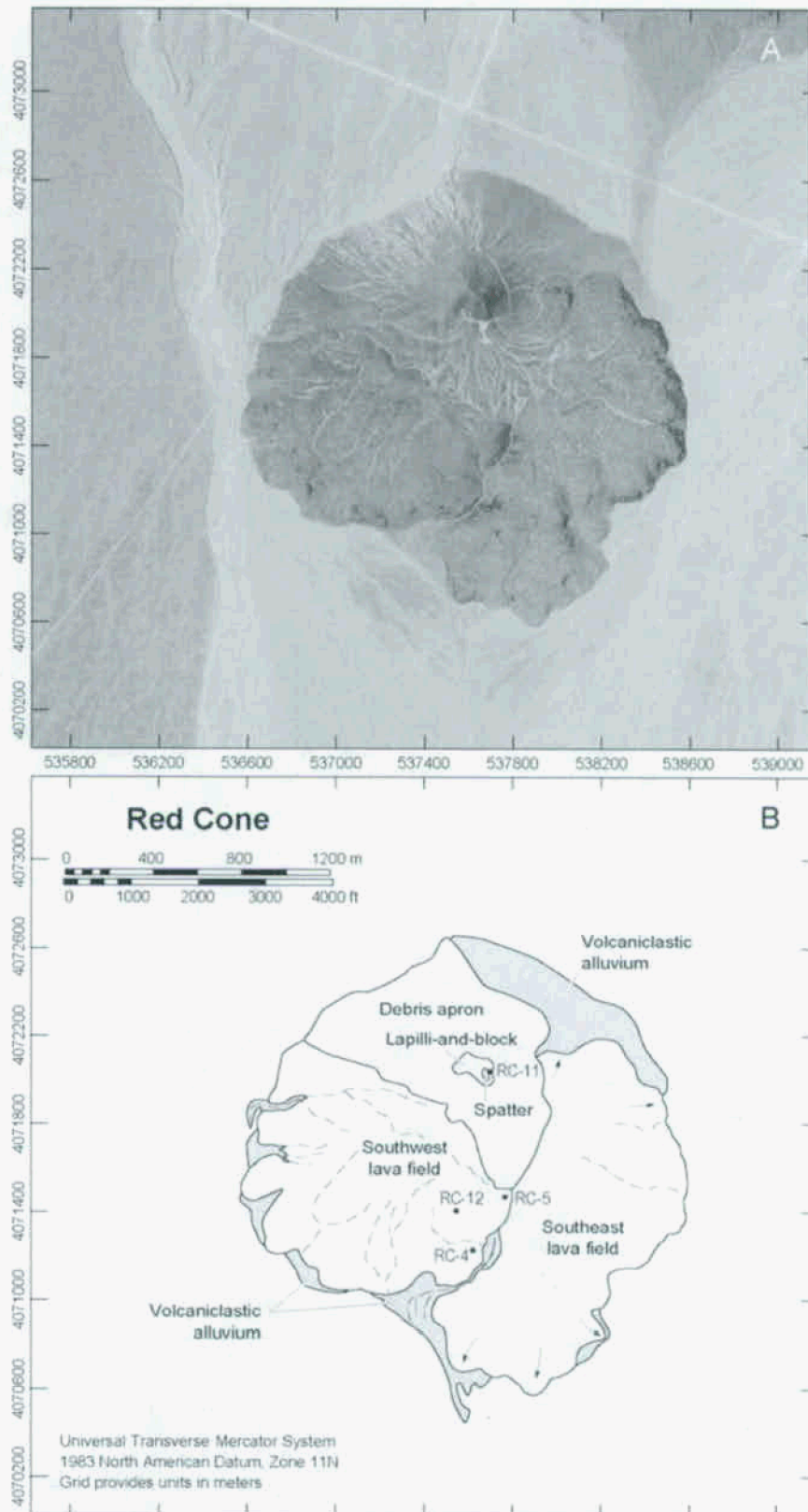


Figure 2



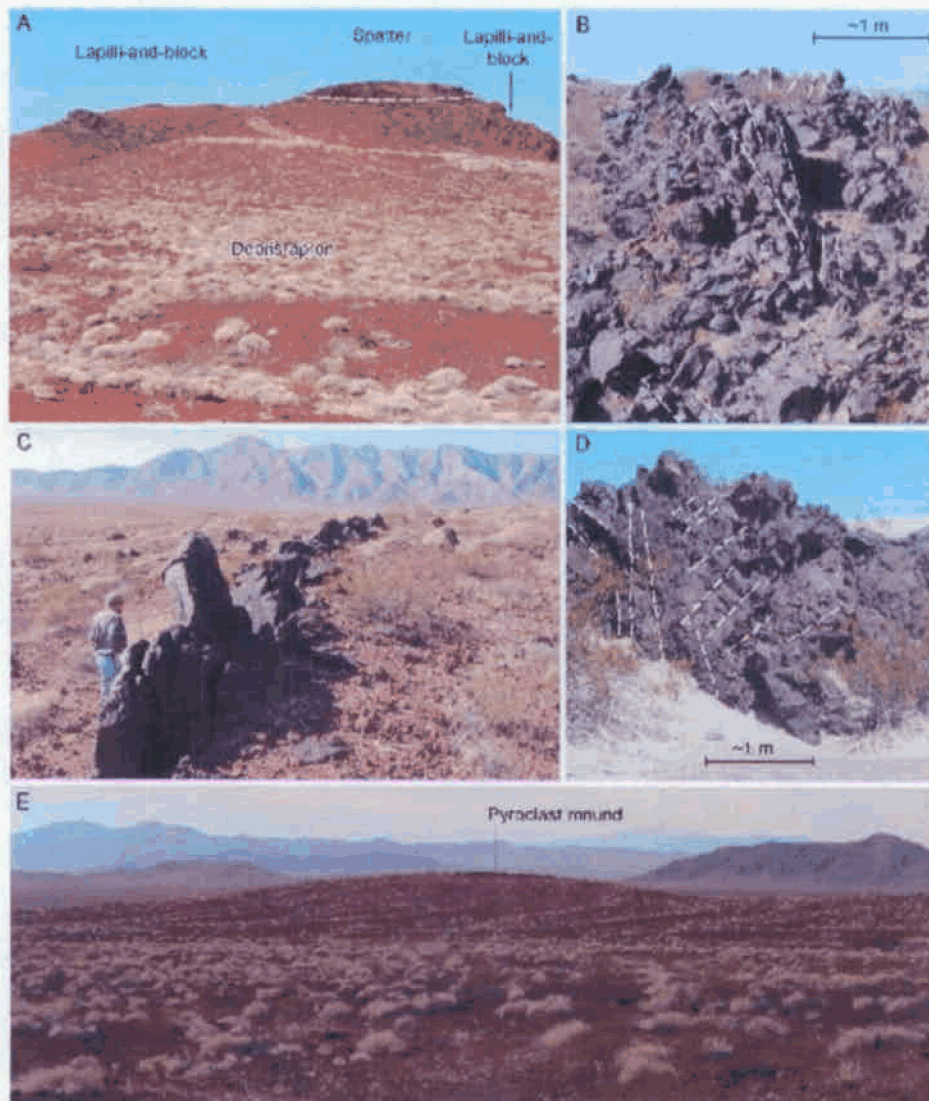


Figure 3



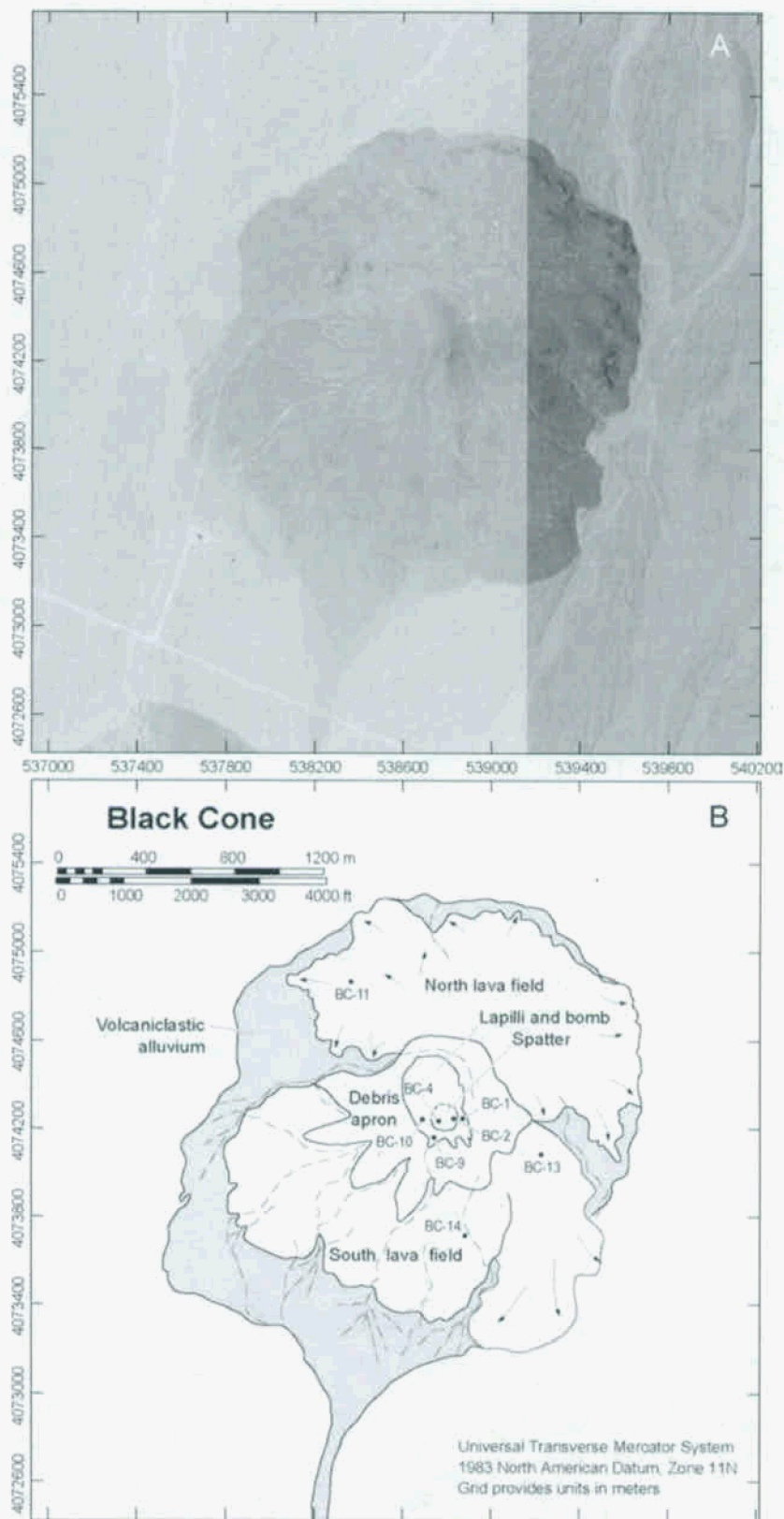


Figure 4

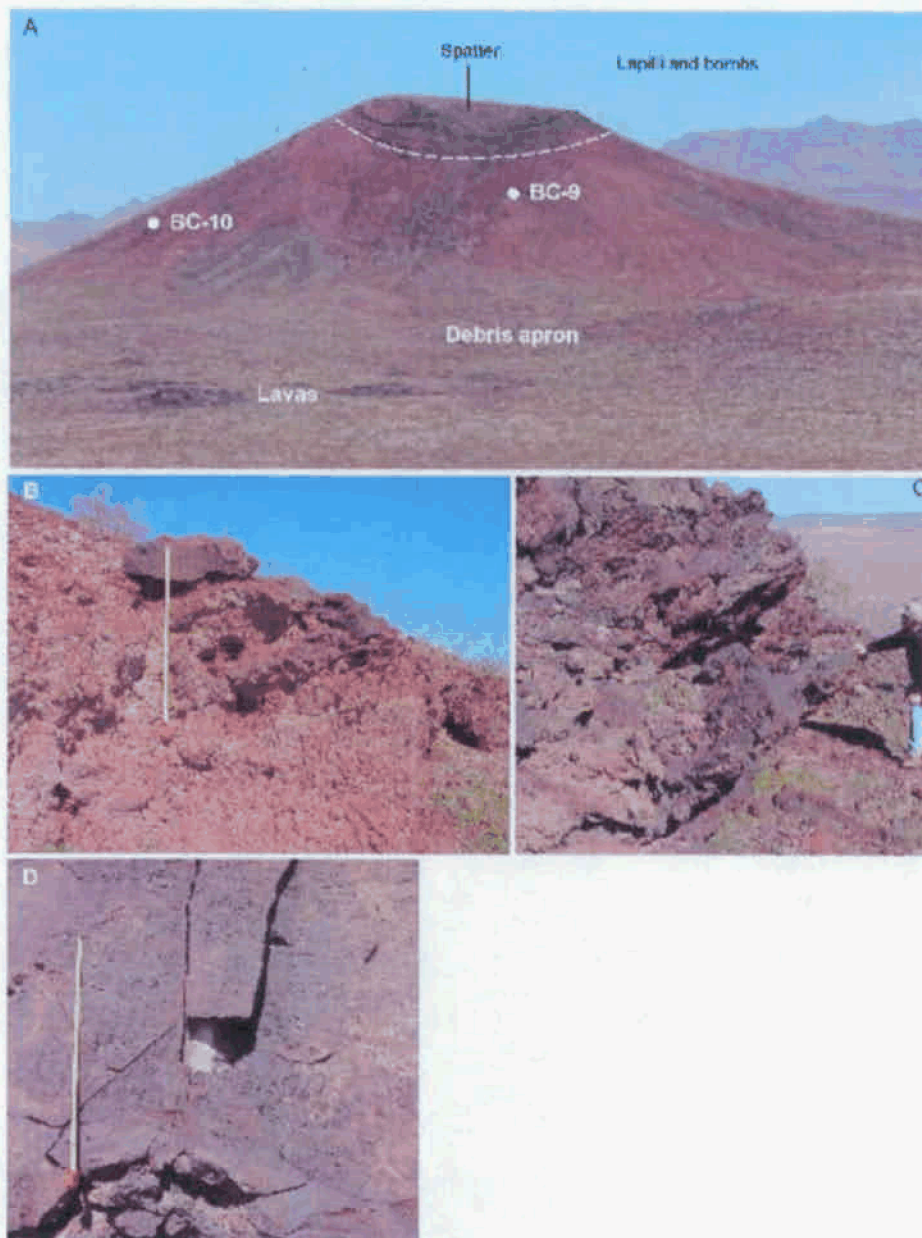


Figure 5

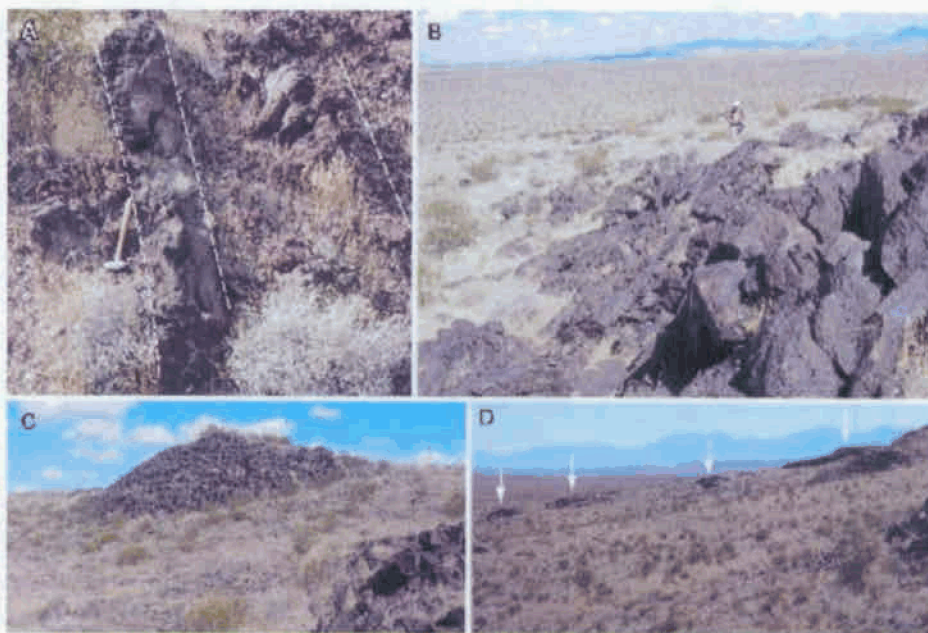


Figure 6

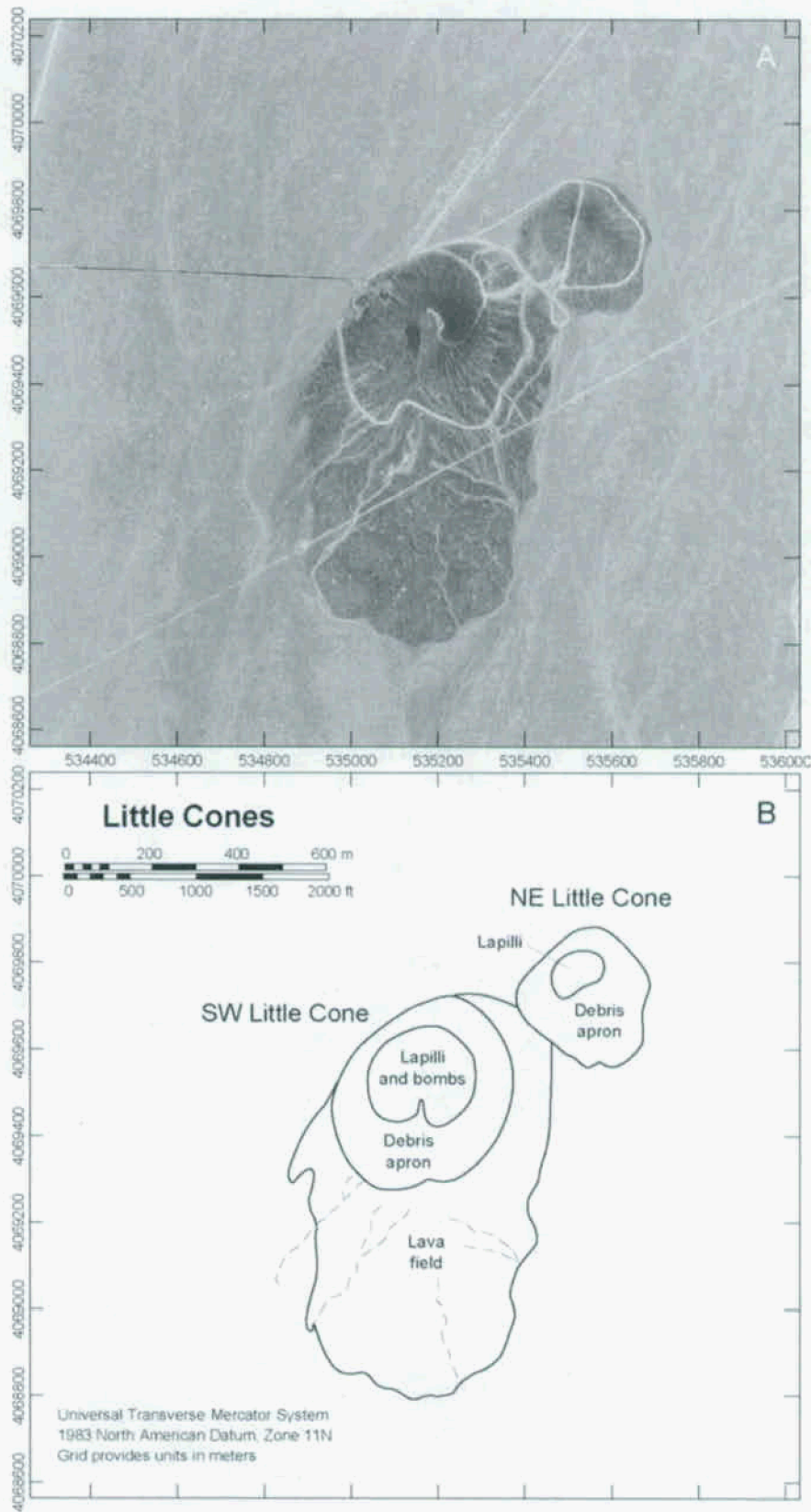


Figure 7



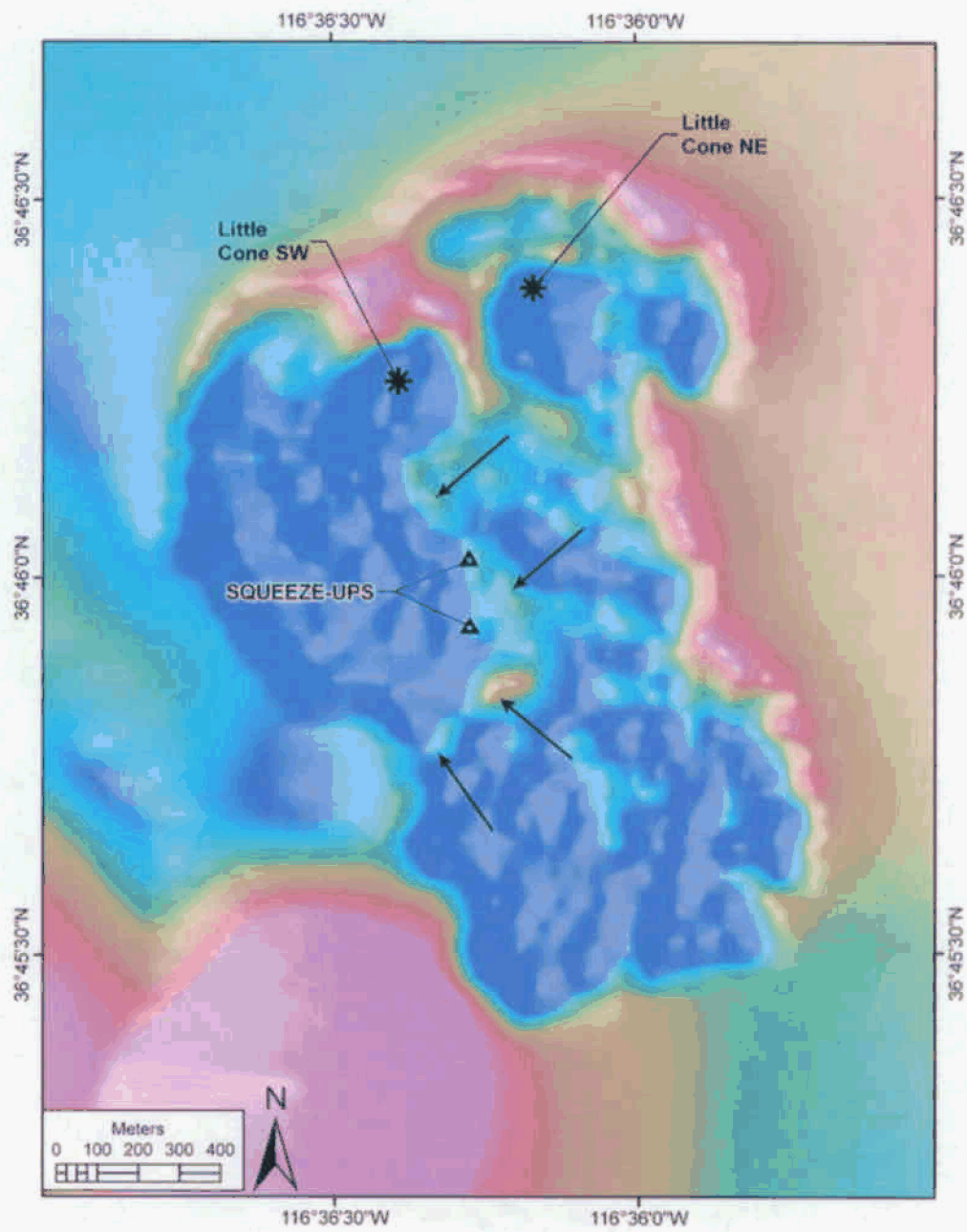


Figure 8

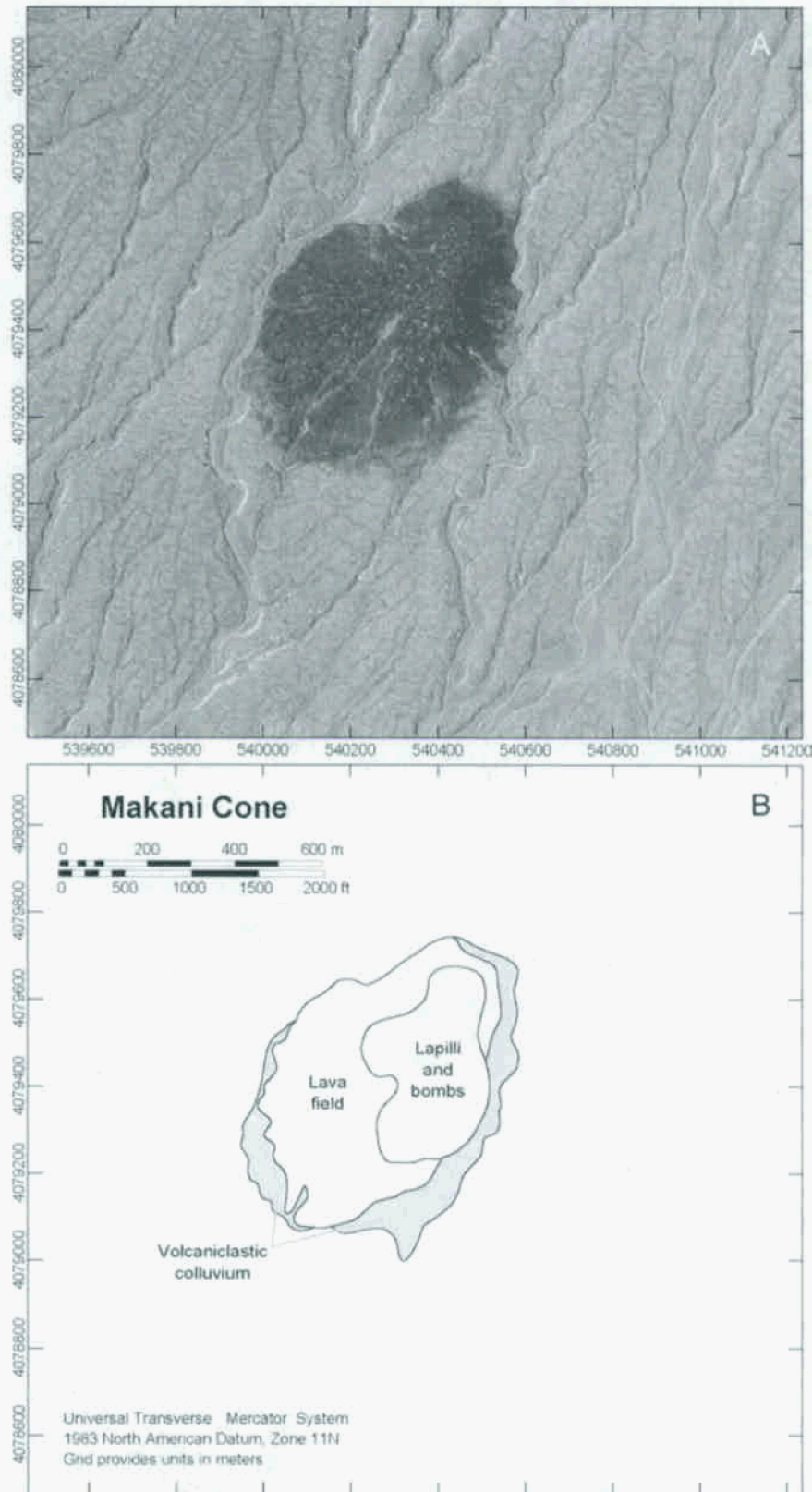


Figure 9

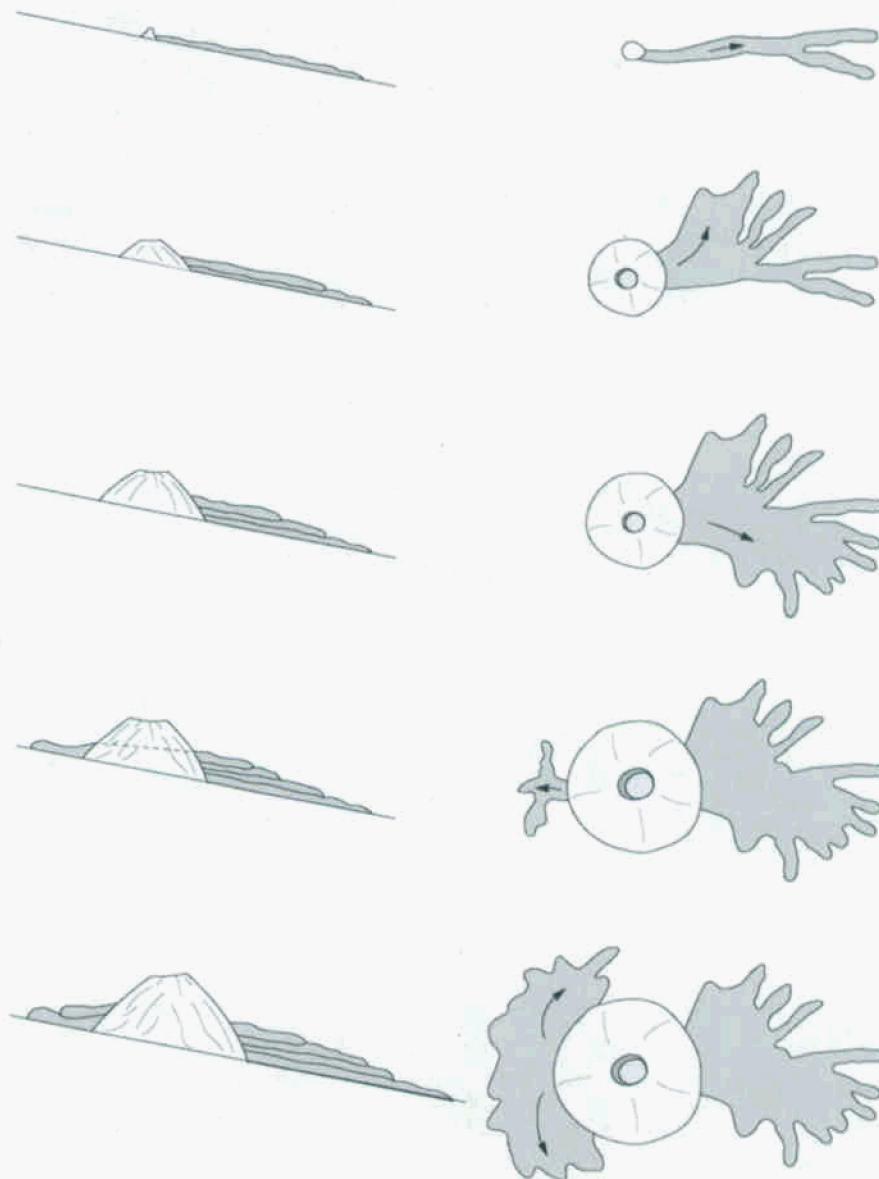


Figure 10

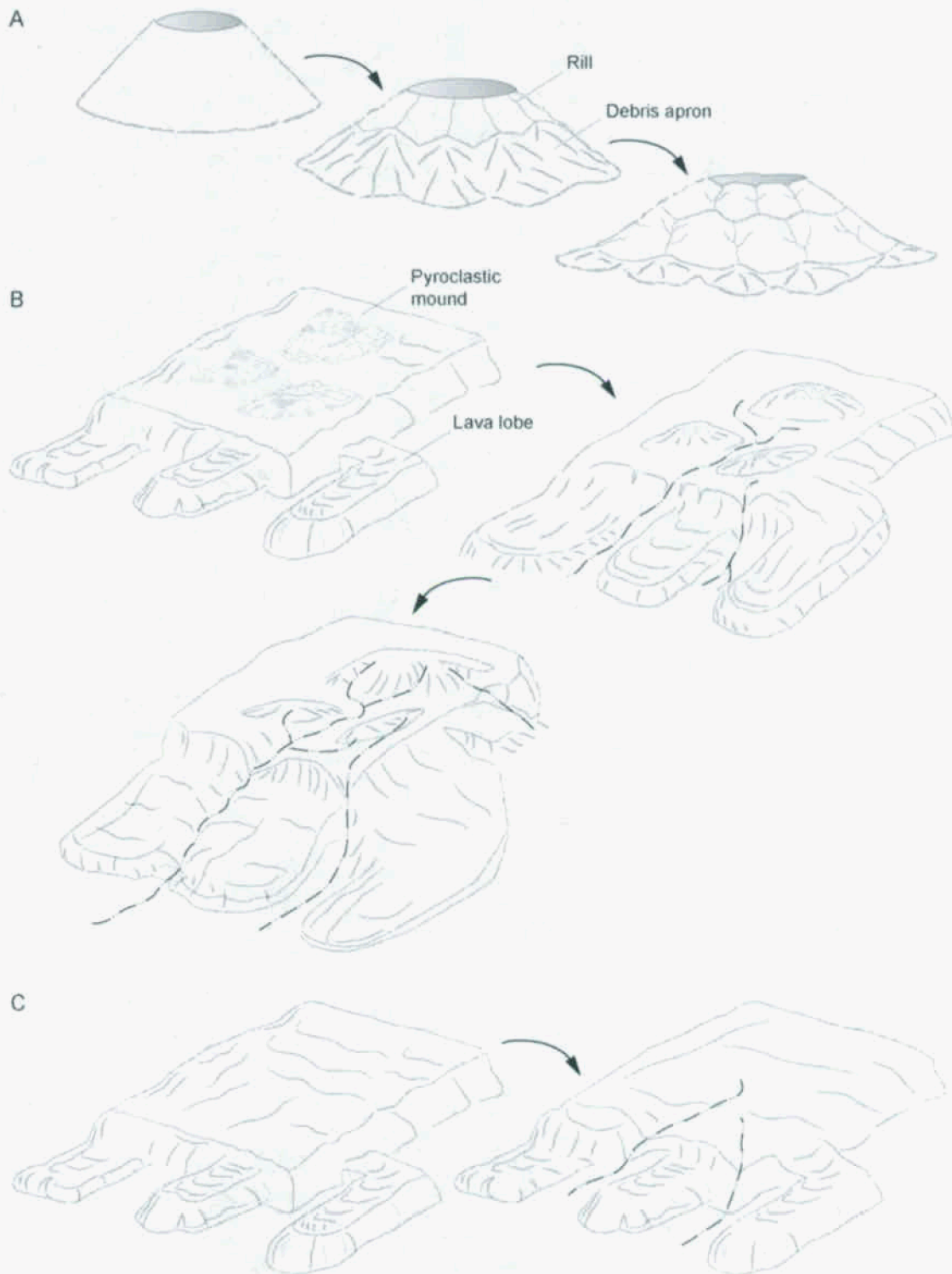


Figure 11



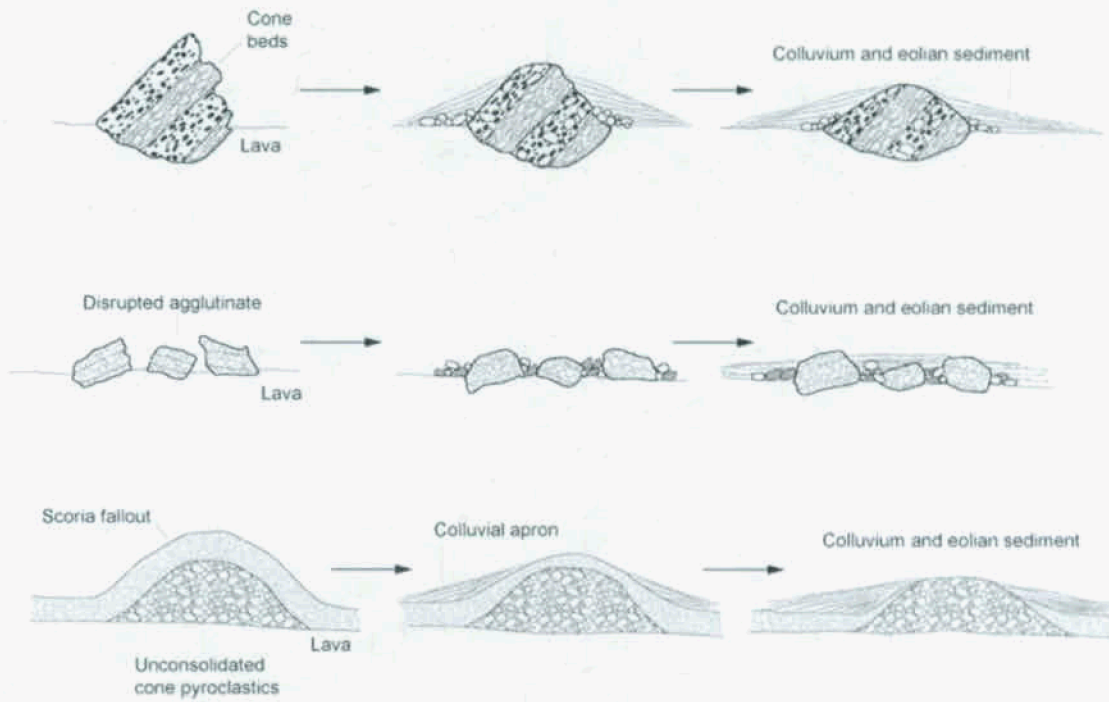


Figure 12